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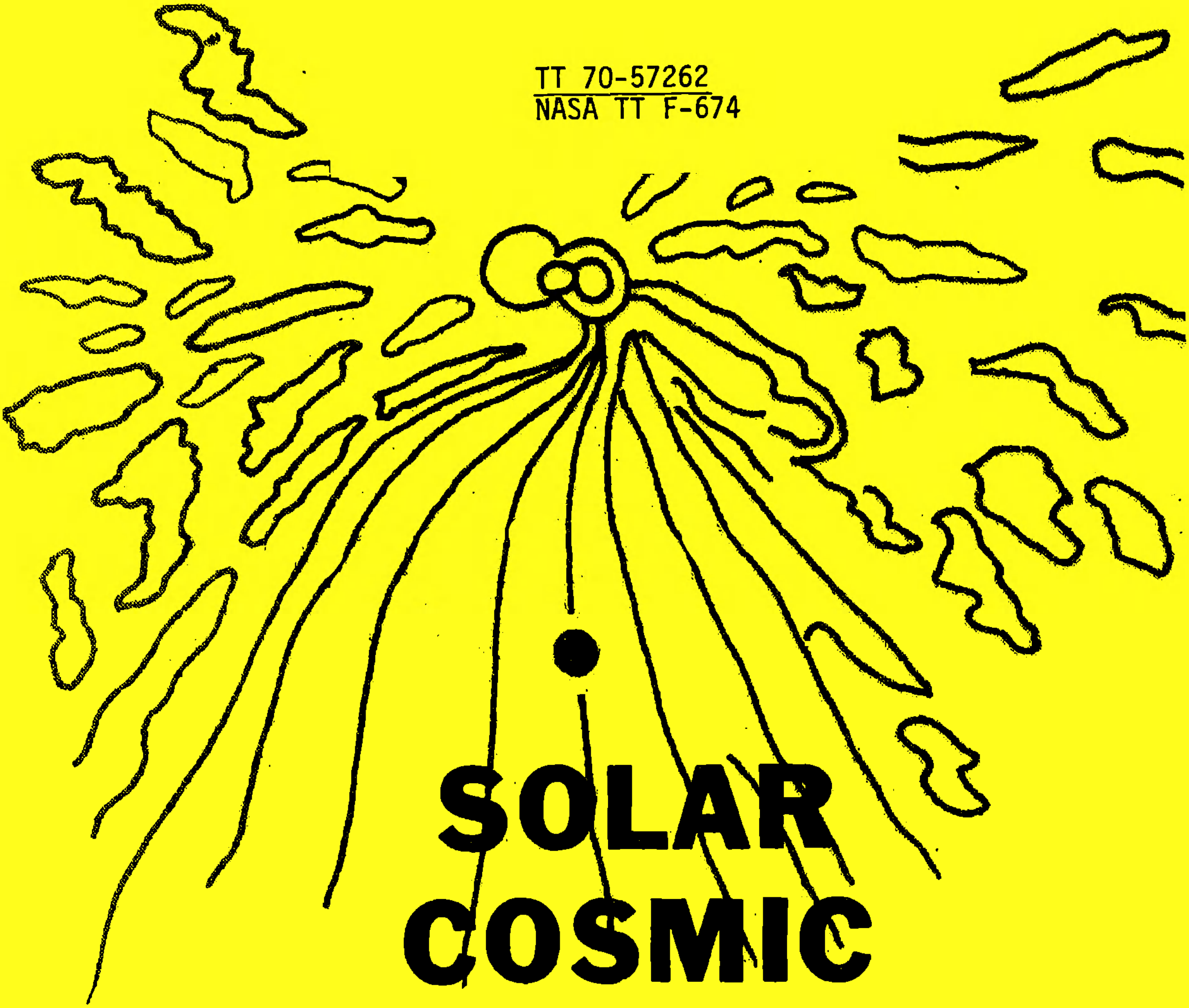

SOLAR COSMIC RAYS

L. I. DORMAN
L. I. MIROSHNICHENKO

TRANSLATED FROM RUSSIAN

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(Solnechnye kosmicheskie luchi)

L. I. DORMAN
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ANNOTATION

In the book "Solar Cosmic Rays" by L. I. Dorman and L. I. Miroshnichenko, voluminous experimental data on solar cosmic rays obtained during 1942-1967 with the help of ground apparatus for continuous recording of cosmic rays (neutron monitors, ionization chambers, scintillation telescopes) have been systematized and analyzed. Stratospheric data and the data gathered from satellite and rocket-borne instruments have also been investigated in this book.

Main attention has been focussed on the problems of generation and propagation of solar cosmic rays. In particular, the question regarding the form of representation of energy spectrum of solar particles (power and exponential function of rigidity) has been examined in detail and the dependence of diffusion coefficient on energy of the particles and distance from the Sun has been discussed.

A separate chapter has been devoted to certain problems of physics of solar flares and generation of cosmic rays on the Sun. Among other things, the possibility of forecasting flares emitting fluxes of energetic particles has been discussed. The problems of protection from solar flare protons during flights of astronauts have been dealt with in a separate section. In "Conclusion" some experimental and theoretical problems related to further study of solar cosmic rays have been pointed out.

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FOREWORD

The investigations on the problems of physics of the Sun, solar and terrestrial relationships and interplanetary space have achieved great importance during the past 10-15 years. It is sufficient to mention the discovery of radiation belts, solar wind, interplanetary magnetic field, etc. Direct measurements of plasma, particles and fields in the interplanetary space are attaining a systematic nature. Moreover, method and technology of terrestrial recording of phenomena associated with the Sun are being improved.

The dynamic nature of phenomena occurring in the interplanetary medium is getting more and more theoretical and experimentally based nowadays. The theoretical and experimentally based nowadays. The interest in the dynamic processes in the interplanetary space is increasing because of its impact on wider problem of solar-terrestrial relationships. As is well known, the Sun is a source of different types of electromagnetic and corpuscular radiations. The electromagnetic radiation propagates from the Sun in straight lines and has an effect only on the ionosphere and upper layers of the Earth's atmosphere. Corpuscular radiation mainly consists of protons and electrons and, therefore, has a strong effect on the terrestrial and interplanetary magnetic fields.

Corpuscular radiation of the Sun can be classified into two major divisions depending upon the energy of the particles. The first type includes the solar wind representing a continuous stream of protons (with equal amount of electrons for keeping the stream electrically neutral) in the energy range of the order of kev. The average velocity of quiet solar wind is approximately equal to 300 km/sec while after powerful chromospheric flares, it can go up to 2000 km/sec. During flares, often high-energy protons (second class of corpuscular radiation) which are usually known as solar cosmic rays due to their great resemblance with cosmic rays of galactic origin are emitted. These protons can have an energy at the Earth's orbit of the order of 10^{-9} - 10^{-8} erg/cm^3. This value is comparable to the density of energy of quiet solar wind and interplanetary magnetic field and is approximately 3-4 orders higher than the density of galactic cosmic rays. From the dynamic point of view, solar cosmic rays can be mostly considered as individual, independently moving particles. But at large dimensions of the interplanetary space, they can be considered as a liquid or gas related to interplanetary magnetic fields just like the gas of galactic cosmic rays in the interstellar medium.

This monograph deals with the mechanism of generation of particles of 10^6-10^{10} ev energy on the Sun, their propagation through interplanetary space and the result of their interaction with the Earth's atmosphere. The scope and content of this monograph are detailed in the table of contents. Although, at present, generation and propagation of solar cosmic rays is known only in general terms, many important problems remain unsolved even up to this time. Hence, the authors tried to collect in the book the existing information on solar cosmic rays to the maximum extent and also include the bibliography on related problems wherever necessary. However, the list of references cannot be considered to be complete and, therefore, in case of necessity, the readers are advised to refer to the original articles on special problems.

Numerous experimental data collected on solar cosmic rays and its analysis on the basis of the latest developments of cosmic electrodynamics and physics of plasma have offered much valuable information about the processes on the Sun, in the interplanetary space and the Earth's environment. Thus, solar cosmic rays became a very sensitive tool for studying many cosmophysical phenomena. The present state of these problems enables us to expect that further achievement are possible in this field in the near future. The importance of the study of solar cosmic rays is increasing every year owing to the necessity of safeguarding astronauts from solar radiations during their flights around the Earth, to the Moon, the Mars and other planets of the solar system.

The authors take this opportunity to express their deep gratitude to E.L. Feinberg and S.B. Pikelner for their interest and valuable suggestions and also to S. N. Vernov, V. L. Ginzburg, S. I. Syrovatskii, M. A. Livshits, N. S. Kaminer, G. F. Krymskii, A. A. Korchak, T. N. Charakhchyan, A. Z. Dolginov, I. N. Toptygin and V. I. Shishov for valuable discussion on a number of problems, considered in the book.

December 1967 L. I. Dorman, L. I. Miroshnichenko

INTRODUCTION

The study of solar cosmic rays has achieved great importance for solving a number of problems of astrophysics, solar physics and geophysics.

Solar cosmic rays are particles (mainly protons) accelerated on the Sun and having an energy $E \gtrsim 10^4 - 10^5$ ev/nucleon. These particles move in the interplanetary space independent of each other in contrast to the particles of solar wind and corpuscular beams with $E \lesssim 10^4 - 10^5$ ev/nucleon which constitute plasma and conform to the equations of magnetohydrodynamics.* Energy spectrum of solar cosmic rays is very steep. Their composition is characterized by practically complete absence of light nuclei. The entire solar system can be the region of propagation of solar particles. In some cases, intensity of their energy at the Earth's orbit is comparable to the intensity of the kinetic energy of plasma and the intensity of energy of interplanetary magnetic fields.

The study of solar cosmic rays is important, particularly, for evaluating the role of stars in general, generation of cosmic radiation and also mainly, for the investigation of the mechanisms of acceleration of particles under cosmic conditions (viz., intensity of the flux of accelerated particles, their energy spectrum, composition of the nuclei, time variations, etc.).

Up till now, a vast amount of observational data has been accumulated on solar cosmic rays in different energy intervals with the help of different measuring equipments inclusive of satellite-borne instruments and cosmic rockets. Detailed data on energy spectrum, nuclear composition and other characteristics of solar cosmic rays were obtained as a result of these measurements.

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* *The lower limit of the energy of solar cosmic rays is tentative. Most probably, there is a gradual transition from the spectrum of plasma particles to the spectrum of higher-energy particles, i.e., particles of solar cosmic rays (see Sections 7, 8).*

Some of the earlier results of investigations on cosmic rays published before 1963 were systematized in L. I. Dorman's book [1.2] and were partially analyzed within the framework of the general problem of variations. However, the increasing tempo of investigations and widening of the field of problems involved enable to consider the study of solar cosmic rays as an important independent problem. The entire complex of processes can be divided into the following four groups: (i) The mechanisms of injection, acceleration and exit of accelerated particles from the region of chromospheric flares; (ii) the mechanisms of propagation of solar cosmic rays in the interplanetary space (viz. diffusion of particles in irregular magnetic fields, capture in magnetic traps, drifting and convective transfer); (iii) the processes relating to the passage of solar cosmic rays in the geomagnetic field (namely, formation of shock zones, effect of latitude, probable capture of solar particles in the circumterrestrial magnetic trap, collective invasion in magnetosphere, interaction with the Earth's variable magnetic field); (iv) interaction of solar cosmic rays with the Earth's atmosphere (additional ionization of the lower ionosphere, nuclear cascade processes in atmosphere).

As mentioned earlier, observation of solar cosmic rays is a sensitive tool for studying the electromagnetic conditions and processes in the Sun's atmosphere, interplanetary space and in the Earth's environment. Very valuable information about the mechanisms of acceleration on the Sun, direction and intensity of interplanetary magnetic fields, magnetic traps of solar particles and structure of the interplanetary medium in general, was obtained from the data on high-energy solar particles much before the advent of rocket and satellite-borne techniques. In particular, the study of time variation of solar particles during the great flare of February 23, 1956 led to the assumption of the existence of irregularities in the interplanetary magnetic field and also made it possible to approximately estimate the intensity and geometry of this field. Later on, direct measurements in the interplanetary space confirmed the results obtained from the flares. At present, it is beyond doubt that electromagnetic field in interplanetary space is one of the basic factors determining space and time distribution of solar cosmic rays near the Earth's orbit.

There is also another important aspect of this problem, namely, safety from solar radiation of the crew of a spaceship during solar flares. In principle, the necessary thickness of protective screens (shields) can be determined on the basis of the existing data on the magnitude and duration of flares, and also by taking into account the spectrum of solar cosmic rays. However, empirical calculations show that safety measures taken by using sufficiently thick shields can lead to a considerable increase in weight of spaceships (e.g. in order to ensure the safety of flight during a flare of the type observed on February 23, 1956, a shield weighing about 379 tons is necessary). In order to make the space flights more safe, reliable criteria should be developed for forecasting the dangerous chromospheric flares which generate cosmic rays. Also, one should be able to predict in advance the magnitude of the flux of solar particles, and the nature of their propagation during their passage through the interplanetary space. In order to achieve the above objective, thorough and systematic investigation of the nature of solar activity and solar cosmic rays should be undertaken.

An attempt has been made in this monograph to compile the available experimental data on solar cosmic rays and to interpret these on the basis of modern concepts of electromagnetic processes on the Sun, in the interplanetary space and in the Earth's magnetosphere.

An historical review of the study of solar cosmic rays is described in Chapter I. The sensitivity of different types of solar particles to physical conditions in the solar atmosphere, interplanetary space and the Earth's surroundings are also considered. A special Section is devoted to experimental details and the methods of investigations of solar cosmic rays.

Geophysical effects of solar cosmic rays -- relation with radiation belts, effect on ionosphere and isotopic composition of air, possible interaction of solar particles with the Earth's magnetosphere and other effects -- are considered briefly in Chapter II.

Chapter III is devoted to evaluation of the latest experimental data on energy spectrum, nuclear composition and time variations in flux of solar cosmic rays on the basis of measurements on the Earth's surface, in stratosphere and cosmic space. The possibility of accumulation of low-energy solar particles in the solar system is considered. The probable relation between solar flares and luminescence of the Moon and the Mercury is described.

Propagation of solar cosmic rays in the interplanetary space is analyzed in Chapter IV. Movement of solar particles in quasiregular and irregular fields of interplanetary space is considered. Different aspects of the elementary diffusion model are analyzed in detail and a kinetic model is described.

Some of the problems concerning the physics of solar flares and generation of cosmic rays on the Sun are considered in Chapter V. Peculiarities of chromospheric flares associated with considerable increases in the flux of cosmic rays on the Earth are described and the possibilities of forecasting such events are discussed. A close relation between emission of fast particles and solar radio emission of type IV is pointed out. Modern theoretical concepts of the mechanisms of origin of solar flares, mechanisms of injection of particles, and the concepts of possible nuclear processes on the Sun are considered. Information on solar electrons and neutrons is very much necessary for a proper understanding of these processes because the generation of these particles on the Sun and their propagation through the interplanetary space have a number of peculiarities as compared to protons. The existing experimental data on fast solar electrons and the possibilities of detecting solar neutrons are described in Chapter V. A special Section is devoted to the problems of safety of astronauts from protons during solar flares.

The important results have been summarized in the Chapter on concluding remarks and some of the problems and aspects of the study of solar cosmic rays have also been outlined.

CHAPTER I

SOLAR COSMIC RAYS AS A SOURCE OF INFORMATION ON ELECTROMAGNETIC STATE OF THE SOLAR SYSTEM

1. HISTORICAL REVIEW

1.1. First four flares of cosmic rays. The study of solar cosmic rays has a history of about 25 years. The first four flares of cosmic rays were recorded on February 28, 1942; March 7, 1942; July 25, 1946 and on November 19, 1949. The data obtained were not sufficiently complete since the flares were recorded by only a small number of stations equipped with instruments intended mainly for the measurement of the μ-meson component. Even during these first earlier observations attention was paid to the correlation between cosmic ray flares and some other solar and geophysical phenomena. For example, during February 28, 1942 outburst, a chromospheric flare was observed for 3 $^1/2$ hours on the Sun. Simultaneously with the above, there was short-wave radio blackout on the Earth and an extremely large geomagnetic storm followed after about 24 hours. The increase in the intensity of cosmic rays on March 7, 1942 was also, most probably, caused by the solar flare since this increase was also accompanied by a blackout of radio communication. The solar flare was not observed visually. The cosmic ray outburst on July 25, 1946, was also caused by a bright chromospheric flare, and was later on followed by a geomagnetic storm. A chromospheric flare was also observed during November 19, 1949 outburst.

In spite of scantiness of the initial data, at least on its basis, it was possible to obtain preliminary information on the spectrum of solar particles, their motion in the interplanetary and terrestrial magnetic fields and about the mechanisms of generation and emission of cosmic rays from solar atmosphere. In particular, it was established that the particles ejected during all the above four flares were charged and had an energy of $\mathcal{E}_K \lesssim 10^9$ ev. The magnitude of the outburst was found to be considerably dependent on the coordinates of the observing station. The upper limit of the Sun's general magnetic field ($H \lesssim 2$ gauss) and of the field of galactic sleeve, in which lies the solar system ($H \lesssim 2 \times 10^{-6}$ gauss) were determined. The differential spectrum of solar particles from November 19, 1949, February 28 and March 7, 1942 flares has been found to be of the form $\varepsilon^{-4} - \varepsilon^{-5}$ (it was not possible to determine the spectrum for July 15, 1946 flare due to inadequate experimental data). The size of the emitting region ($\gtrsim 10^{10}$ cm) and the total number of accelerated particles ($\sim 10^{32}$), were determined for November 19, 1949 flare. These results are well in conformity with the statistical mechanism of acceleration suggested by Fermi. The data on the first four flares are systematically described in the book by L. I. Dorman [1].

1.2. February 23, 1956 flare. The most powerful of all the cosmic ray flares observed up to this time took place on February 23, 1956. It was recorded by a large number of stations equipped with different instruments and as a rule, meant for recording various secondary components of cosmic rays [1,2].

Experimental observation have revealed that for this flare during the initial stages, there was not only a strong anisotropy of incident radiation but also a relatively large difference ($\sim$ 10 minutes) in the beginning of the increase of intensity at different places on the Earth's surface. The delay of 10 minutes corresponds to the difference in the order of energy of different particles and cannot be due to differences in the sensitivity of instruments. According to Lüst and Simpson [3], the propagation time of the particles in the geomagnetic field is of the order of 0.1 second. Therefore, it is natural to relate the observed large difference in the delay to the propagation time of particles from the Sun to the Earth. A similar effect was also observed during November 19, 1949 flare event. It is worth mentioning that on February 23, 1956, the intensity of cosmic rays reached the maximum value (about 50 times the normal intensity of neutron component at sea level) in about 10 minutes after the commencement of the sudden outburst. After about an hour, the flux of solar particles started decreasing approximately following the law $\sim t^{-3/2}$ (time is counted from the commencement of the outburst).

A number of models have been suggested by Meyer et al. [4], L.I. Dorman [5] and Brown [6] to explain these facts. They were all based on the assumption of the existence of disorderly magnetic fields in the interplanetary space in which diffusion of particles takes place. This basic assumption, put forward in one or another form, is an inseparable part of all the modern models of propagation of solar cosmic rays.

Meyer et al. [4] suggested that around the Sun and the Earth, there is a spherical cavity of thickness 1.4 a.u. in which the intensity of the magnetic field H is of the order of $H \lesssim 10^{-6}$ gauss. This cavity is surrounded by a region of disorderly field ($H \sim 10^{-5}$ gauss) of thickness 5 a.u. Beyond it, there is the orderly field of galactic sleeve with $H \sim 10^{-5}$ gauss. A part of the cosmic rays generated during flare is propagated directly towards the Earth. The other part, reflected from the region of disorderly field, reaches the Earth in the form of a scattered beam with some time lag. If the transport range for scattering in the disorderly field is $\Lambda \gtrsim 10^{12}$ cm, the intensity of cosmic rays will decrease within the cavity according to the law $\sim t^{-3/2}$ because of diffusion of particles from the cavity free from magnetic field, into the interstellar space through the region of the disorderly field. In addition to the model of Meyer et al. [4], Brown [6] suggested that the scattering of particles within the cavity due to turbulent magnetic fields frozen in the solar corpuscular beams should also be considered.

L.I. Dorman [1,5] assumed that the solar particles diffuse in whole of the space between the Sun and the Earth. In order to conform to experimental observations, it is necessary to assume the value of transport range as $\Lambda \lesssim 10^{13}$ cm. It is important to mention that the intensity of solar particles on the Earth's surface should decrease not according to power law but according to an exponential law after they reach the edge of the scattering region and start entering the interstellar space freely (see Section 14.3). According to L.I. Dorman [5], effective radius of scattering region for the particles of February 23, 1956 flare is estimated to be $r_0 \gg 5$ a.u.

1.3. Study of flares from the data of the world network of stations and stratospheric measurements. Investigations on solar cosmic rays got a new fillip owing to the creation of the world network of stations on the eve of the International Geophysical Year (IGY) (1957-1958). This network is functioning even at present. Owing to this network, it became possible to study different flares of cosmic rays in detail and to relate them to different geophysical and heliophysical phenomena.

In the recent past, research workers paid attention not only to the biggest flare on February 23, 1956 but also to cosmic ray flares observed during July 1959, May and November 1960 by the world network of stations. The small outbursts of cosmic rays of amplitude $\lesssim$ 1% in the neutron component are of great interest. Although this effect was first observed by Firor [7] much earlier than the beginning of the International Geophysical Year, a detailed statistical investigation became possible only after a vast amount of observational data was available through the world network of stations. The study of small flares is important not only for selecting the models of propagation of solar particles but also to find out whether fast particles are also generated during all the chromospheric flares. This problem has become very complicated and the results of different authors do not agree.

During the year 1962-67, the world network of stations was reequipped with new instruments having large range of detectors and high statistical accuracy (up to 0.1% on recording for 2 hours). One of these sophisticated instruments is the neutron supermonitor described by Carmichael [8].

Valuable information about cosmic ray flares has been obtained by measurements made in the regions of high latitudes and in stratosphere at high altitudes with the help of geophysical balloon- and rocket-borne equipment. Effects of flares in the staratosphere were investigated even before the beginning of the International Geophysical Year (for example, by Pomerantz [9], Neer and Anderson [10]. In particular, Winckler's observations [11], taken with the help of balloons after the lapse of a lot of time after the beginning of February 23, 1956 flare, made it possible to determine the spectrum of solar particles in the region of low rigidities. However, the most complete information was obtained during subsequent years. The existence of magnetic traps for particles in front of the solar corpuscular beams was established by Ney et al. [12] and A.N. Charakhch'yan et al. [13] only as a result of measurements conducted in the stratosphere in May, 1959. Stratospheric measurements by Yates [14] during November 12-13, 1960 flare made it possible to record, for the first time, relativistic solar α-particles with $\varepsilon_k \geqslant 560$ Mev/nucleon.

Commencing from the middle of 1957 (coinciding with the beginning of the International Geophysical Year) routine stratospheric measurements were made in the Soviet Union under the guidance of A.N. Charakhch'yan at Murmansk (geomagnetic latitude 64°N) and Moscow (51°N) and at Simeiz (41°N) from April 1958 onwards. More than 10,000 flights were carried out by A.N. Charakhch'yan's group during 1957-1966. A total number of 26 cosmic ray flares were recorded in stratosphere during the period 1958 and beginning of 1962 and out of them 23 flares were observed by A.N. Charakhch'yan's group in the Murmansk region [15].

1.4. Various methods of detecting solar particles. It is well known that an increase in the flux of ultraviolet radiation during chromospheric flares considerably increases the degree of ionization in ionosphere towards the sun-lit side of the Earth. It partially or even completely blacks out the radio communications on short waves. Another cause of the high-latitude ionization (polar cap ionization) in ionosphere was detected during the flare February 23, 1956. It has now been established [2], that the polar cap absorption of short radio waves may also be caused due to the propagation of solar protons with ε_k = 10-100 Mev to the Earth. Particles having such high energy penetrate only into the polar regions of the Earth and give rise to an increase in the absorption of cosmic radio noise and also of short radio waves from ground stations. The phenomenon of polar cap absorption (PCA) has been studied by continuous recording of the intensity of cosmic radio noise at a frequency of 27.6 MHz by a special equipment called riometer. The riometer was first built by Little and Leinbach [16] and was later improved both in the USA and the Soviet Union and afterwards in many other countries. At present, continuous recordings of cosmic noise are undertaken at other fixed frequencies as well. Apart from riometric observations, valuable information on the lower end of the spectrum of solar particles is provided by other ionospheric methods (Bailey [17]) and also by the observation on diffusion aurora at polar caps (luminescence of excited gases of the Earth's atmosphere) and on α-rays produced as a result of nuclear interactions between solar particles in the atmosphere. Bailey [17] and Brown [18] have shown that the intensity of these radiations directly depends upon the spectral characteristics and total flux of solar cosmic rays.

The advent of cosmic rockets and artificial Earth satellites have opened vast possibilities of direct determination of flux of extremely low-energy solar particles in the interplanetary space and offers a new tool for studying solar cosmic rays.

The first cosmic-ray flare was observed by E.V. Gorchakov and G.A. Bazilevskaya outside the Earth's atmosphere on July 7, 1958 with the help of the third Soviet Earth satellite [19]. A little later (September 12-13, 1959 during the flight of the second Soviet cosmic rocket, L.V. Kurnosova et al. [20] recorded a short-lived intense outburst of cosmic rays which had the maximum increase for nuclei of charge $Z \geq 15$. This was interpreted as an indication that conditions favorable for generation (or exit from the limits of solar corona) of heavy nuclei are created during certain flares. A similar short-lived flare was recorded by L.V. Kurnosova et al. [22] during the flight of the third Soviet spaceship on December 1, 1960.

The flare of September 28, 1961 is of exceptional interest. This flare was recorded by American research workers Bryant et al. [23] on "Explorer-12" satellite in a wide energy range and for a long duration outside the Earth's magnetosphere.

Rocket and satellite observation provided much information about low-energy solar cosmic rays which were inaccessible to observations with the help of balloons. The data on nuclear composition at great height are of great interest since they are not distorted by interactions in the residual atmosphere (which is inevitable in the case of observations by balloons). Very valuable information about spectrum and composition of solar cosmic rays was obtained by Biswas et al. [24] as a result of emulsion measurements on rockets over Churchill during November 15, 1960 flare event. According to Biswas et al. [24], Similar rigidity spectra are obtained for protons, α-particles and nuclei of C, N, O and have the form $\exp(-R/R_0)$ where the characteristic magnetic rigidity R_0 for all the nuclei lies within the limits of 85-100 Mev. The nuclear composition of particles thus obtained was found to be approximately the same as composition of solar atmosphere.

Yoshida et al. [25] obtained interesting result on the increases in the intensity of solar protons with $\mathcal{E}_k > 18$ Mev and $\mathcal{E}_k > 30$ Mev during October 1959 and February 1961 with the help of "Explorer-7". In all, 23 flares were recorded during this period. It was shown that, in accordance with the theory of isotropic diffusion, the flux of protons after attaining a maximum value starts decreasing according to the law $\sim t^{-3/2}$. Bryant et al. [26], also observed three more events of outbursts of the beam of solar particles by means of "Explorer-12" (September 10, 1961 and November 10, 1961; this satellite also recorded the above-mentioned flare event of September 28, 1961) and "Explorer-14" (October 23, 1962). According to the observations made by Van Allen et al. [27] on "Mariner-2", 13 small flares of cosmic rays were observed between August and December 1962. Most probably, these flares caused by solar protons having energies $\mathcal{E}_k = 0.5$ - 10 Mev.

Recently, a new method of investigating cosmic rays -- study of isotopes obtained by bombarding satellite body (or special samples of a substance) with cosmic rays -- was developed (for example, see the works of Waddington and Freier [28], Lal et al. [29].

The separation of beams of solar and galactic cosmic rays is based on the characteristic difference in their spectra. Solar particles have a steeper spectrum than those of the galactic particles, i.e., the beam of cosmic rays from the Sun is rich in low-energy particles. Hence the passage of solar particles through the space is usually accompanied by ionization losses whereas in the case of galactic cosmic rays, there will be considerable increase in the number of nuclear-active particles. Meteoritic method is also based on similar considerations (for example, see the review of Geiss et al. [30]). In particular, the work of Yokoyama and Mabuchi [31] describes the results of calculating the rate of formation of some radioactive nuclei having comparatively low half-life period in chondrites during nuclear reactions with solar cosmic rays. The role of different types of reactions in the formation of cosmogenic nuclei is estimated. It is shown that large amounts of radioactive nuclei Co^{60}, Ni^{59}, Cr^{51}, Ca^{41}, Cl^{36} are formed in chondrites as a result of nuclear reactions with secondary neutrons. The relative role of reaction (n, γ) is 30% in the formation of Cl^{36}, 50-70% for Co^{60}, Ni^{59}, Cr^{51}, Ca^{41} and 100% for Ca^{45}. The value of the intensity of the beam of slow neutrons necessary for the formation of these isotopes is determined.

Measurements on radioactivity of Al^{26} in sediments of the Pacific Ocean, taken by Lal and Venkatavaradan [32], showed that the radioactivity is much more than that could be expected as a result of nuclear interactions of cosmic rays in the Earth's atmosphere. It is postulated that the additional radioactivity observed is related to the fact that micrometeorites reaching the Earth contain Al^{26} which is produced as a result of bombardment of the substance of micrometeorites with powerful particles in the interplanetary space. Low-energy protons, generated on the Sun during flares can be such particles. A stable beam of galactic cosmic rays cannot give rise to this effect. In order to explain the observed radioactivity of Al^{26}, the average flux of low-energy protons ($\mathcal{E}_k > 10$ Mev) in the interplanetary space at a distance of 2 a.u. from the Sun must be 100 cm^2 sec^{-1} during the last 10^5 years.

2. METHODS OF STUDYING SOLAR COSMIC RAYS

Let us consider some peculiarities in the methods of the study of solar cosmic rays.

2.1. Determination of spectrum in different energy ranges. Spectrum of solar particles in a wide range of energies can be directly measured even beyond the limits of atmosphere and magnetosphere by equipment placed on board the satellites having extremely long stretched-out orbit and on cosmic rockets. For example, during September 28, 1961 solar flare the satellite "Explorer-12" was situated at a distance of about 80,000 km from the Earth's center on the subsolar side which made it possible to measure differential spectrum of protons with $\varepsilon_k \geqslant 2$ Mev (lower limit of sensitivity of the apparatus) for about two days after the chromospheric flare [23].

One of the methods of studying the spectrum of solar particles (for example, see A.N. Charakhch'yan's work [15]) is measurement of absorption of solar particles in upper layers of the atmosphere. The intensity of galactic cosmic rays in stratosphere is maximum at altitudes of 16-22 km. At greater altitudes, their intensity is reduced considerably. However, during flare events, solar cosmic rays do not have a maximum intensity in stratosphere at high altitudes: it increases gradually with altitude. Knowing the number of particles measured at different altitudes before and during flares, it is possible to plot the so-called absorption curve, i.e., the dependence of the number of solar particles recorded vs. the stratospheric pressure. Information on the intensity of primary radiation can be extrapolated from the above curve up to a pressure of 5 g/cm^2 which corresponds to the range of protons having energy $\varepsilon_k = 90$ Mev. However, this method is applicable only to energies up to a few hundred Mev. Information on solar particles having an energy less than a few tens of Mev, which cannot be observed directly with the help of balloons, can be obtained from the data on the ionosphere effects of these particles (see Chapter II).

The spectrum of particles in the high-energy region can be determined from data obtained at ground. Since geomagnetic field during a solar flare and a few hours after it is practically undisturbed, normal values obtained by Quenby and Wenk [33] by taking into account the effect of penumbra can be taken as the values of threshold rigidity. For this purpose, it is also possible to make use of the results of calculations recently done by Shea et al. [34] by considering the asymptotic cones of propagation of particles. Existence of entry zones should also be taken into consideration. Determination of spectrum is considerably improved by considering the isotropic nature of a flare.

Following is one of the methods of determining spectrum from ground data suggested by N.S. Kaminer [35].

If one defines the spectrum of solar particles in the form $D(p) \sim p^{-\gamma}$ (p is the momentum of the particle) and taking into account the coefficients of proportionality, it is possible to calculate the intensity I_{γ}^{i} for every i-th observation point at any value of γ. Let us denote the ratio of the calculated value of intensity I_{γ}^{i} to the experimental value by $a_i(\gamma)$. In order to maintain the constancy of this ratio, let us use the parameter

$$A(\gamma) = \frac{1}{m} \sum_{i=1}^{m} | \lg a_i(\gamma) - \overline{\lg a(\gamma)} |,$$

where

$$\overline{\lg a(\gamma)} = \frac{1}{m} \sum_{i=1}^{m} \lg a_i(\gamma).$$

In this case, the value of γ at which $A(\gamma)$ is minimum will be approximately equal to the actual value.

The analysis of May 4, 1960 flare on the basis of the above method showed: (1) the index γ within the range R = 1-5 Gv is approximately equal to 5 ± 0.5 which is in conformity with the measurements on other flares; (2) γ tends to decrease with time.

Another method of determining the spectrum, suggested by L.I. Dorman and L.I. Miroshnichenko [36] is based on the application of the latitude effect. If $m^i(R, h)$ is the integral multiplicity factor of generation of the i-type secondary particles recorded at level h from some primary particle (proton) of rigidity R, and $D_c(R)$ is the particle spectrum of particles from the Sun, then the intensity measured at a point with geomagnetic threshold R_{min} will be equal to

$$I_c^i(R_{\min}, h) = \int_{R_{\min}}^{\infty} D_c(R)\, m^i(R, h)\, dR. \tag{2.1}$$

Differentiating (2. 1) with respect to R, we get

$$D_c(R) = -\frac{\partial I_c^i/\partial R}{m^i(R, h)}. \tag{2.2}$$

Replacing the symbols n and μ by parameters corresponding to neutron and rigidity components, on the basis of (2.2), we get the ratio

$$\frac{\partial I^n/\partial R}{\partial I^\mu/\partial R} = \frac{m^n(R)}{m^\mu(R)}. \tag{2.3}$$

In order to determine the spectrum, it is necessary to find out the multiplicity factor of generation of secondary components at different heights of observation. For a general case when rigidities for stations at sea level R_1 and R_2 do not coincide, with the rigidities R_3 and R_4 for mountainous stations and if the spectrum of solar particles has the form $\sim R^{-\gamma}$, it is possible to use the formula (2.3). Then, in place of (2.3) we get

$$\frac{(\Delta I/\Delta R)_0}{(\Delta I/\Delta R)_h} = \left(\frac{R_*}{R_h}\right)^{-\gamma} \frac{m(R, 0)}{m(R_h, h)}, \tag{2.4}$$

where $(\Delta I/\Delta R)_0$ is the change in intensity at sea level on changing the rigidity by $(\Delta R)_0 = R_1 - R_2$; $(\Delta I/\Delta R)_h$ is the same parameter at an altitude h in the atmosphere while $(\Delta R)_h = R_3 - R_4$; $R_* = 1/2\,(R_1 + R_2)$ and $R_h = 1/2\,(R_3 + R_4)$ (strictly speaking, inequality $R_1 > R_* > R_2$ and $R_3 > R_h > R_4$ should be satisfied). Thus, in order to determine the spectrum, it is first necessary to find out the integral multiplicity factors m^n and m^μ at sea level. To this end, an expression similar to (2.2) as applicable to galactic cosmic rays has been used in [36].

Recently, neutron monitor data on latitude effect was obtained by Rose et al. [38] on "Atka" ship during 1955, i.e., during the period of minimum solar activity and was once again processed in the work of Baduell et al. [37] on the basis of the corrected values of threshold rigidity suggested by Quenby and Wenk [33].

On the basis of the data obtained by Simpson et al. [39], it is possible to find that effective area of a standard neutron monitor is equal to 1.85×10^4 cm^2. The spectrum of primary cosmic radiation in the region $R \geqslant 8$ Gv changes with the cycle of solar activity to a comparatively lesser extent [2]. The amplitude of 11-year variations in the neutron component at sea level is $\leqslant 30\%$. The above result enables us to assume that the flux of neutrons at sea level for stations with $R_{min} \geqslant$ 8 Gv remains constant (within the limits $\leqslant 30\%$) during a solar cycle. In order to reduce the latitudinal curve [37] to absolute units, let us, for example, make use of the data obtained at Bueno Aires station ($R_{min} = 11.4$ Gv). The average counting rate of neutrons at this station in September 1957 was of the order of 18,600 pulses/hour. Hence, the flux of neutrons at effective area of monitor $\sim 1.85 \times 10^4$ cm^2 is equal to 2.9×10^{-4} cm^{2}. sec^{-1}. Relating this value to the latitudinal curve [37], the absolute values of neutron flux for other stations are obtained (Table 2.1).

TABLE 2.1

List of stations used in [36] and their characteristics

Stations	Height above sea level, m	Threshold rigidity, Gv [33]	Flux of neutrons at minimum solar activity, cm^{-2}.sec^{-2}
Ottawa	0	1.05	4.38×10^{-4}
Chicago	0	1.91	4.32×10^{-4}
Wellington	0	3.19	4.21×10^{-4}
Bueno Aires	0	11.4	2.90×10^{-4}
Climax	3500	3.08	4.15×10^{-3}
Peak Sacramento	3000	5.1	3.85×10^{-3}
Mexico City	2200	10.0	3.05×10^{-3}
Huancayo	3400	13.7	2.5×10^{-2}

Fig. 2.1 shows the effect of latitude on the flux of neutrons ($\times 10^4$) at sea level [37] in absolute units and on correlation coefficient W. Estimates [36] show that curve 1 in Fig. 2.1 can be considered reliable with an accuracy $\lesssim 30\%$.

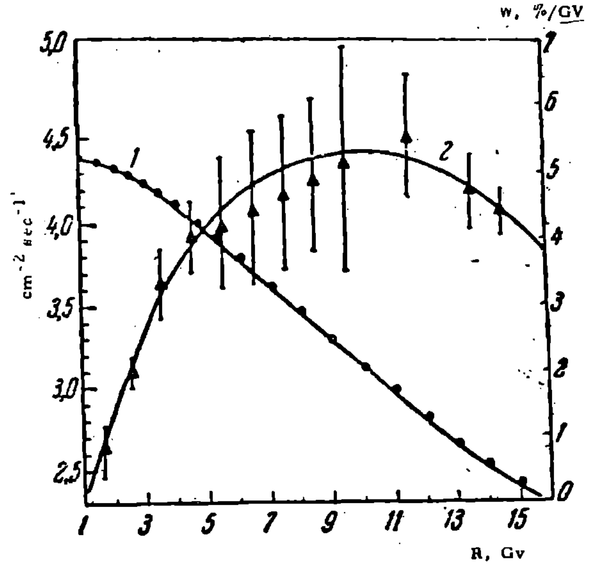

Fig. 2.1. Curve showing the effect of latitude (1) on flux of neutrons($\times 10^4$) and correlation coefficients (2) [37].

The multiplicity factor for generation of neutron component at sea level was calculated in [36] on the basis of the differential spectrum of primary cosmic radiation at minimum solar activity obtained by Elliot et al. [40]. This spectrum is shown in absolute units in Fig. 2.2 by taking McDonald's

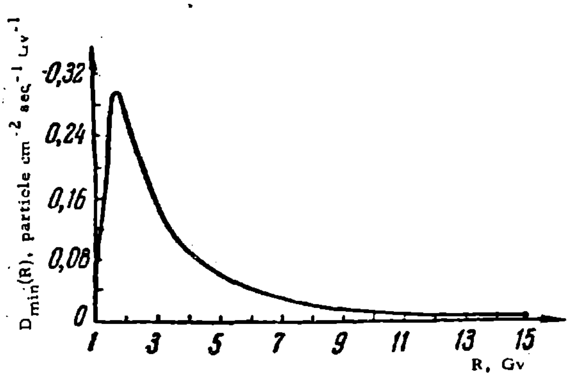

Fig. 2.2. Differential spectrum of primary cosmic radiation depending upon hardness near minimum solar activity (1965) [40].

measurements [41] into account. Results of calculating $m^n(R, 0)$ are shown in Fig. 2.3. It follows from Fig. 2.3 that the multiplicity factor in the interval R = 1 - 10 Gv increases ~ $R^{2.5}$ and at higher rigidities, the increase is even slower.

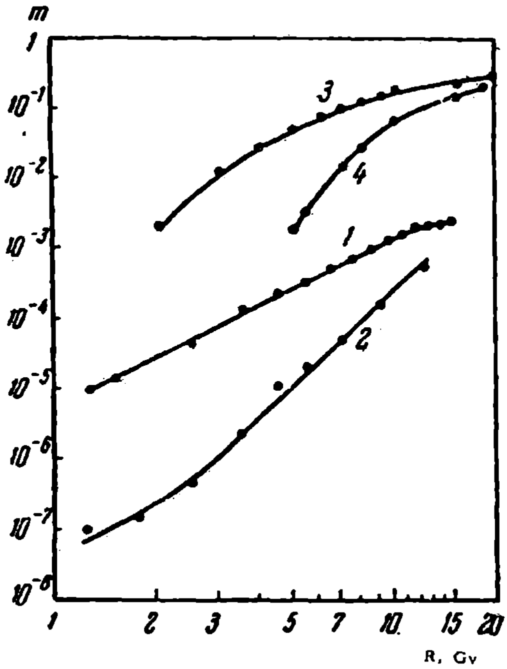

Fig. 2. 3. Integral multiplicity factor for generation of neutron (1) and rigid (2) components of secondary cosmic radiation [36]; 3 and 4 are similar curves taken from [42] for comparison.

In order to calculate $m^{\mu}(R, 0)$, the latitudinal curves obtained for February 23, 1956, flare were used in [36]. These curves were obtained by Quenby and Wenk [33] from the data of 23 stations on neutron and rigid components at sea level and pertain to 0600UT (universal time) on February 23, 1956, i.e., the curves correspond to the period of isotropy. Transforming these curves into absolute units and using formula (2.3), it is possible to calculate (R, 0) (curve 2). Multiplicity factors for generation of neutron (curve 3) and rigid (curve 4) components at sea level, obtained by Webber and Quenby [42] at rating N^i (> 15 Gv) = 100 on the basis of the earlier values of rigidities suggested by Quenby and Webber [43], are also shown for comparison; it should be pointed out that the same primary spectrum obtained by Elliot et al. [40] at the reference value of

D_{min} (15 Gv) = 100 is used in [42]. Correlation coefficients shown in Fig. 2.1 in the range R = 4-11 Gv considerably differ from the values obtained by Webber and Quenby [42] and also by L. I. Dorman [1]. A comparison of curves 1 and 2 with curves 3 and 4 in Fig. 2.3 confirms this discrepancy which, however, is more related to the form of curves than to the absolute values of m^n and m^μ [36] and is almost completely caused by the standard used in [42].

It should be pointed out that the curves 1 and 2 were obtained directly from experimental data which included the total beam of primary cosmic rays without considering the nuclear compositions whereas curves 3 and 4 were calculated by Webber and Quenby [42] with the help of special algebraic transformations and only for primary free protons. In this case, multiplicity factors obtained directly from experimental data for the total beam of primary cosmic rays were used in [42]. The experimental data were, however, normalized in the above-mentioned way. The algebraic transformation used in [42] is simple owing to the fact that rigidities for protons and nuclei with $Z \geqslant 2$ have an elementary relation. As a matter of fact, assuming that the bond energy of nucleons in a nucleus with $Z > 1$ is small at energies of cosmic rays, it can be shown that if the energy of nucleons remains constant, rigidity of nuclei with $Z \geqslant 2$ is double the rigidity of protons. Therefore, multiplicity factor for the generation of a neucleon in a nucleus of rigidity R can be considered equal to the corresponding value of multiplicity factor for a free proton of rigidity R/2. From this follows an important relation [42] for nuclei with $Z \geqslant 2$:

$$m_Z(R,\ h) = A_Z m_p(R/2,\ h), \tag{2.5}$$

where m_p is the multiplicity factor of generation for a free proton and A_Z is the mass number.

Obviously, the total multiplicity factor of generation by considering (2.5) will be the sum

$$m(R,\ h) = m_p(R,\ h) + \sum_{Z \geqslant 2} K_Z A_Z m_p(R/2,\ h), \tag{2.6}$$

where K_Z is the relative abundance of nuclei with charge Z in each interval of rigidities with respect to the abundance of protons taken as unit. According to Webber [44], the number of protons in the given range of rigidities is half than that of necleons brought to the Earth by all the particles of cosmic radiation. Therefore, equation (2.6) can be rewritten in the form

$$m(R, h) = m_p(R, h) + m_p(R/2, h). \tag{2.7}$$

After obtaining the m(R, h) curve directly from experimental data, it is possible to calculate $m_p(R, h)$ as well as $m_{Z \geqslant 2}(R, h)$ for every nucleus with $Z \geqslant 2$ on the basis of equations (2.5) and (2.7) with the help of the special algebraic transformation [42].

Since it is known from experiment that $m_p(R, h)$ is always an increasing, or in any case, nondecreasing function of R, the condition $m_p(R/2, h) \leqslant m_p(R, h)$ should be satisfied at every value of R. Taking it into consideration, we get an important result from (2.7) :

$$m_p(R, h) \leqslant m(R, h) \leqslant 2m_p(R, h), \tag{2.8}$$

i.e., the calculated values of m(R, h) can differ from m_p (R, h) by not more than two times.

It should however be pointed out that protons constitute half of all the nucleons only in galactic cosmic rays. A large number of measurements show (see [2], Section 50.11) that, although nuclear composition of solar cosmic rays for $Z \geqslant 2$ remains practically constant and reflects the relative abundance of elements in the solar atmosphere, the ratio of the flux of protons to the total flux of nuclei with $Z \geqslant 2$ changes within wide limits. In the case of some flares, fluxes of protons and nuclei with $Z \geqslant 2$ reflect the composition of the solar atmosphere while in other cases a surplus of protons. Hence, we can derive analytical expressions for multiplicity factor of generation by considering the nuclear composition of solar cosmic rays. Experimentally established results on the similarity of rigidity spectra of solar cosmic rays and nuclei with $Z \geqslant 2$ (see a review of corresponding works in [2]; Section 50.11] enable us to describe the spectrum of all solar particles by one equation:

$$D_c(R)=D_p(R)+\sum_{Z>2} b^c_Z D_p(R), \tag{2.9}$$

where D_p (R) is the spectrum of protons and b^c_Z is the content of nuclei with specific value of Z as compared to protons. Basing on the same assumptions which were made while deriving the formula (2.5), we can write :

$$m^c(R,\ h)=m_p(R,\ h)+a_c m_p(R/2,\ h), \tag{2.10}$$

where $a_c = \sum_{Z\geqslant 2} A_Z b^c{}_Z$ is the number of nucleons in nuclei $Z \geqslant 2$ per solar proton (the index "c" denotes that the corresponding values of m have been calculated from the data on the flux of solar particles). In this case, obviously, it can be assumed as before that $m_p(R/2) \lessapprox m_p(R)$. However, $m^c(R,\ h)$ and $m_p(R,\ h)$ cannot be related to each other by a simple equation of the type (2.8) because the parameter a_c can change considerably (by more than one order) in one and the same rigidity range for different flares ([2]; Section 50.11). In the case of solar cosmic rays, the following relation will be satisfied :

$$m_p(R,\ h)\leqslant m^c(R,\ h)\leqslant(1+a_c)\, m_p(R,\ h). \tag{2.11}$$

On the basis of (2.10); it is possible to write

$$m^c(R/2^k,\ h)\doteq m_p(R/2^k,\ h)+a_c m_p(R/2^{k+1},\ h), \tag{2.12}$$

where k = 0, 1, 2, 3,. From this, for $m_p(R,\ h)$, we get a alternating series

$$m_p(R,\ h)=\sum_{k=0}^{\infty}(-1)^k a_c^k m_c(R/2^k,\ h), \tag{2.13}$$

from where for the particular case $a_c = 1$ (i.e., for galactic cosmic rays) we have

$$m_p(R,\ h)=\sum_{k=0}^{\infty}(-1)^k m(R/2^k,\ h). \tag{2.14}$$

Calculations of the multiplicity factor of generation $m_p(R,\ h)$ from data on flares of solar cosmic rays, i.e., calculations made with the help of (2.13) on the basis of the values of m_c (R, h) are possible only if the relative nuclear composition of solar particles, i.e., the value of a_c, is known. However, values of only m_c (R, h) were determined in [36] since measurements on nuclear composition of solar particles were not taken during February 23, 1956 flare.

It should be mentioned that the results [36, 42] were obtained on the basis of the values of R for vertically falling primary particles. On the other hand, it is known that detectors of secondary radiation, installed deep in the atmosphere, are sensitive to products of primary radiation included within the limits of certain solid angle (approximately within the limits of $+ 30^0$ with the vertical). Therefore, the dependence of cut-off rigidity used in the works[36, 42] can be considered as a sufficiently good approximation to the effective value of R while recording data at the sea level and on mountains.

On the basis of the calculated values of m^n, differential spectrum of the beam of solar particles was obtained in [36] in absolute units at the atmospheric boundary (Fig. 2. 4) for 0600, 1000, and 2000 UT on February 23, 1956 (the flare started at 0342 UT, the maximum was observed at 0350 UT and at 0500 UT the beam of solar particles became isotropic). Data of the following pairs of stations from Table 2. 1 were used in calculations : Ottawa - Chicago, Chicago - Wellington, Climax - Sacramento, Sacramento - Mexico. The straight lines in Fig. 2. 4 have an inclination corresponding to $\gamma = 6$.

It is interesting to mention that the spectrum obtained has a tendency to change the inclination with a change in the rigidity but within the limit of experimental error, it does not change its form with the passage of time. For example, the rigidity spectrum at 0600 UT can be represented in the form $\sim R^{-3}$ within the interval 1-2. 5 Gv but on increasing the rigidity to 10 Gv, it becomes very steep ($\sim R^{-7 \pm 0.5}$). This last result is in conformity with the results of other investigations. For example, L. I. Dorman [1] and Meyer et al. [4] obtained spectrum of the scattered beam of solar particles in the form $D_c \sim \varepsilon^{-7}$ (ε is the total energy of the particles in Gev) from which one obtains $D_c \sim R^{-7}$ for relativistic energies. According to the work of Baduell et al. [37], the effective spectrum of variations of primary radiation was defined by the relation $D_c(R)/D(R) \sim R^{-4.5}$ (where $D \sim R^{-2}$ is the spectrum of undisturbed primary beam in the range of rigidities considered) from which it follows that D_c (R)~ $R^{-6.5}$ and this is in line with the curves shown in Fig. 2. 4.

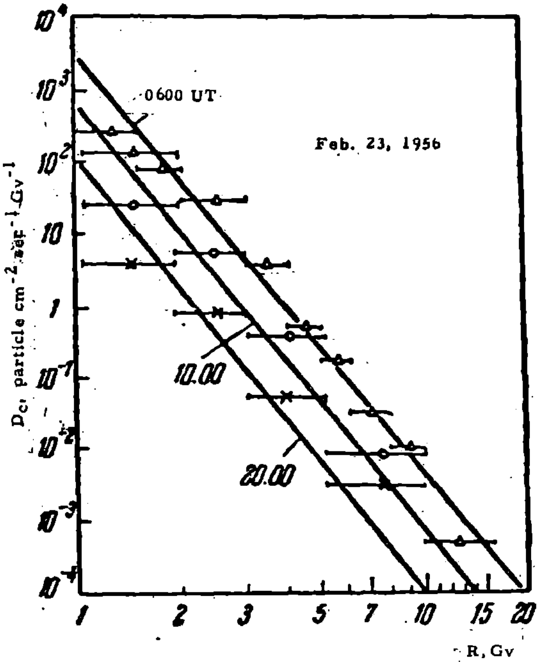

Fig. 2 4 Differential rigidity spectra of solar particles at 0600, 1000 and 2000 UT on February 23, 1965 [36]. The straight lines have an inclination corresponding to $\gamma = 6$.

Satisfactory agreement of the obtained results with othe investigations confirms the applicability of the above-described method for determining multiplicity factor of generation and spectrum of solar particles beyond the limits of the Earth's atmosphere in the range of $R \leqslant 15$Gv.

The accuracy of the determination of γ obviously depends on the width of the rigidity interval $R_1 - R_2$ for which the flux b of secondary particles of a particular type at the given altitude of observation is known from the data on the effect of latitude. If the spectrum of solar cosmic rays is of the type $D_c = D_0 R^{-\gamma}$, the following relation should obviously be satisfied:

$$\int_{R_1}^{R_2} b\,dR = D_0 \int_{R_1}^{R_2} R^{-\gamma}\,dR. \tag{2.15}$$

from which we get

$$D_0 = \frac{b\,(R_2 - R_1)(1 - \gamma)}{R_2^{1-\gamma} - R_1^{1-\gamma}}. \qquad (2.16)$$

Putting $D_0(R)^{-\delta} = b$, we get the value of $\bar{R}$:

$$\bar{R} = \left(\frac{b}{D_0}\right)^{-1/\gamma} = \left[\frac{(R_2 - R_1)(1 - \gamma)}{R_2^{1-\gamma} - R_1^{1-\gamma}}\right]. \qquad (2.17)$$

Thus, from equations (2.15) and (2.17), it is possible to get the values of D_0 and $\bar{R}$ at known b and given γ and also to evaluate ΔD_0 and $\Delta\bar{R}$ on changing γ and vice versa.

Another significant aspect should also be pointed out. If $D_c = D_0 R^{-\gamma}$, from (2.1) we get the relation

$$I_c^l(R_{\min}, h) = D_0 \int_{R_{\min}}^{\infty} R^{-\gamma} m^l(R, h)\,dR = D_0 f(R_{\min}, \gamma, h). \qquad (2.18)$$

If the dependence of m^l on R is known at all values of R, it is possible to calculate auxiliary functions

$$f(R_{\min}, \gamma, h) = \int_{R_{\min}}^{\infty} R^{-\gamma} m^l(R, h)\,dR \qquad (2.19)$$

for different values of $R_{\min}$ and γ. By comparing the curves obtained from equation (2.19) with the experimental latitudinal curves during a flare, we get direct indications about the value of γ (it is valid only for the period of isotropy).

2.2. Barometric effect of neutron component during flares. By increasing the accuracy of continuous recording of cosmic rays and by making detailed comparisons of variations in cosmic rays at different stations, Dorman's method [1, 2] of determining the barometric effect with the help of one coefficient, corresponding to some mean free path for absorption of average beam of cosmic rays, is not sufficient. As a matter of fact, the spectrum of particles falling into the Earth's atmosphere can change considerably during certain types of variations in cosmic rays and may lead to a considerable change in the properties of secondary component, particularly, to a change in the mean free path for its absorption in the lower part of the atmosphere, i.e., to a change in the barometric coefficient. In particular, significant changes in the barometric coefficient take place during large increases in the intensity of cosmic rays produced during strong chromospheric flares. It is necessary to consider precisely the barometric effect during these very periods and, first of all, this effect is important in the case of neutron component which has high barometric coefficient.

Let λ_g and λ_s be the mean free paths for absorption of neutron component generated by galactic and solar beams of cosmic rays respectively; I and p be the counting rate of neutron monitor and pressure at the observation point before the flare and I_s and $p+\Delta p$ be the counting rate and pressure during the flare. If it is assumed that the intensity of galactic cosmic rays does not change during flare*, according to McCracken [46], the relative change in the counting rate, reduced to standard pressure p_o, is determined from the relation

$$A=\left(\frac{I_s(p+\Delta p)}{I(p)}\exp\frac{\Delta p}{\lambda_s}-\exp\frac{\Delta p}{\lambda}\right)\exp\frac{p-p_0}{\lambda}, \qquad (2.20)$$

where

$$\lambda^{-1}=\lambda_s^{-1}-\lambda_g^{-1}. \qquad (2.21)$$

The parameter λ_s for neutron component was, for example, measured in the works of Santochi et al. [47] and Sakurai and Maeda [48]. A value for λ_s = 137 g/cm2 has been suggested in L.I. Dorman's book ([1], Section 40.3) for the rigid component on the basis of the data for November 19, 1949 flare.

Taking λ_s = 100 g/cm^2 and λ_g = 138 g/cm^2 for the neutron component, from (2.21) we get λ = 363 g/cm^2. If p differs from p_o by approximately 40 g/cm^2, the second factor in equation (2.20) gives a coefficient of 1.12. In order to estimate the importance of determining the barometric correction accurately during flares, the data on the percentage increase in the intensity of neutron component of cosmic rays on November 15, 1960 at seven stations at sea level and the average quadratic dispersion of these data for three cases is shown in Table 2.2: A — when barometric correction is not introduced at all; B — when the correction is calculated by the usual method; C — when calculations are done on the basis of formula (2.20).

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* *In some cases, this assumption is not fulfilled (for example, flare occurring during Forbush effect). In such a case, it is necessary to introduce another third mean free path for absorption related to modulated beam of particles.*

TABLE 2.2

Comparison of different methods of introducing barometric corrections during 0500-0600 UT on November 15, 1960 [46]

Station	A	B	C
Churchill	61.5	61.1	64.1
College	69.4	67.9	66.4
Mauson	65.0	65.5	65.0
McMurdo	67.1	66.6	66.6
Ottawa	69.1	66.9	66.9
Resolute	57.3	58.2	63.8
Thule	66.8	67.5	64.4
Average quadratic dispersion	4.3	3.6	1.2

It is obvious from Table 2.2 that a proper introduction of barometric correction, to a large extent, changes the observational data by reducing the average quadratic dispersion of the data of different stations by about 2 times (in the case of isotropic propagation of solar particles).

Strictly speaking, a similar situation will be observed during Forbush effects and other time variations. However, the magnitude of these variations is considerably less than the effects of flares, and the spectrum of particles subjected to these variations does not differ much from the spectrum of undisturbed beam of galactic cosmic rays and the application of formula (2.20) is not very much different from the usual method. Even then, in a number of cases -- from study of the precise structure of variations, study of microvariations, data of supermonitors having low statistical error, and determination of the spectrum from high-latitude data (when a small difference in the readings of two stations may be considerably distorted due to fluctuations in pressure) -- it becomes necessary to use the method of two mean free paths (or even three mean free paths on superimposing the effects) according to equation (2.20).

In view of the importance of the problem, N.S. Kaminer [49] attempted to verify the results obtained by McCracken [46]. In the work [49], the following equation was obtained in place of equation (2.20):

$$A = \left[\frac{I_A}{I_g(p_0)} \exp\frac{\Delta p}{\lambda_g} - \exp\left(-\frac{p-p_0}{\lambda_g}\right)\exp\frac{\Delta p}{\lambda}\right]\exp\frac{p-p_0}{\lambda_g} \qquad (2.22)$$

or

$$A = \frac{I_A}{I_g(p_0)} \exp\frac{p-p_0+\Delta p}{\lambda_A} - \exp\frac{p-p_0+\Delta p}{\lambda_g} \qquad (2.23)$$

The following conclusions can be drawn from comparison of expressions (2.22) and (2.20):

1) The last term in (2.20) contains the parameter λ_g in place of λ_s in (2.22). The difference is considerable since the ratio $\lambda_g / \lambda_s \sim 3$-$3.5$.

2) The effect of the flare in equation (2.20) is exprèssed in terms of I(p) -- average counting rate at the given station before the flare. But, if in accordance with [46], the standard pressure p_0 is considered for all the stations, the value of I(p) corresponding to a pressure p before a flare becomes an arbitrary (random) parameter. Therefore, it is more accurate to express the relative increase in the counting rate during a flare by the parameter $I_{s(p_0)}/I_{(p_0)}$ Considering that the differences in the values of p for stations situated

at sea level can go up to ~ 40g/cm^2, we can replace the ratio $I_s(p_o)/I(p_o)$ by $I_s(p_o)/I(p)$ which may lead to an error of a few percents in the magnitude of the effect.

It should be mentioned that in practice the barometric effect during flares of cosmic rays requires a knowledge of the mean free path for absorption of solar component λ_s. At the same time, this parameter depends upon the spectrum of solar cosmic rays. Therefore, λ_s can be different for different flares and moreover, λ_g for a given flare will depend on the threshold of geomagnetic latitude [49].

The other point made by N.S. Kaminer [49] refers to the following. The results of analysis obtained on different flares of cosmic rays must be comparable. Moreover, if the standard value of pressure p_{o1} is used for analyzing the data of one flare and p_{o2} for analyzing the data of another flare, the subsequent generalization of these results will obviously be difficult. Hence, it is desirable to establish one standard value p_o on the basis of the data on average values of pressure $\bar{p}$ for all the world network of stations situated near the sea level and to use the same in all the investigations. For example, if it is considered that the stations situated near the sea level are those whose altitude changes within 0-500 m, the average pressure $\bar{p}$ changes from 1010 millibars to 960 millibars. In this case, p_o = 980-990 millibars should be taken as the average standard value of pressure.

Assuming (for example, see [46]) that detectors of high-latitude stations during isotropic phase of a flare record equal increases in intensity, N.S. Kaminer [49] from an analysis of the data of world network of cosmic-ray stations situated at sea level found a simple relation for the value of λ_s :

$$\frac{1}{\lambda_s}=\frac{1}{(p^m+\Delta p^m)-(p^n+\Delta p^n)}\left\{\frac{\dfrac{I_s^n}{I^n(p_0)}-\exp\left(-\dfrac{p^n-p_0+\Delta p^n}{\lambda_g}\right)}{\dfrac{I_s^m}{I^m(p_0)}-\exp\left(-\dfrac{p^m-p_0+\Delta p^m}{\lambda_g}\right)}\right\}. \tag{2.24}$$

where m and n relate to the indices obtained from data of two different stations.

In view of these experimental problems, the data obtained by Kodama [50] during recording on different amplitudes of the increase of neutrons of different multiplicity factors are of great interest. This result was obtained during January 28, 1967 flare which was recorded by the naval triple-counter monitor of the type described in [8] during the stay of ice breaker "Fuji" at Siova (69.03° S, 39.60° W). Table 2.3 shows amplitudes of the increase and average energies of nucleons responsible for the given multiplicity factors.

TABLE 2.3

Amplitude of the increase at different multiplicity factors at Siova during January 28, 1967 flare [50]

Multiplicity factor	1	2	3	4	5	$\geqslant 6$
Average energy, Gev	0.11	0.24	0.52	1.0	1.7	$\geqslant 4.0$
Amplitude of the increase, %	14.7	17.6	15.4	11.4	9.0	$\leqslant 2.1$

2.3 Analytical method of studying the flares. An interesting method was suggested by Shea and Smart [51] for studying the effects of flares from ground data. This method makes it possible to consider the possible anisotropy of solar cosmic rays while analyzing the observation data (for which it is necessary to know the receiving cones of primary radiation for ground stations and integral multiplicity factors of generation for the observed secondary components). Following is the principle of the method. The amplitude A of the increase expressed in per cents can be represented by the equation:

$$A = \frac{\sum_R S(R, x) D_f(R) F(\theta, R)}{\sum_R S(R, x) D_q(R)}, \qquad (2.25)$$

where S is the specific work function, R is the rigidity, x is the atmospheric depth, D is the spectrum and F is a function describing the angular dependence between direction at the visible source and asymptotic direction for every value of the rigidity; indices q and f refer to quiet and disturbed (during flares) spectra respectively. Analyzing the data of every station and summing up all the rigidities with an interval of 0.01 from the smallest observed rigidity (in order to consider the penumbra effect) to a value at which further increase is insignificant, it is possible to get the propagation direction, flux and spectrum of particles. The results computed for the May 4, 1960 flare event are well in conformity with the experimental data. One advantage of this method lies in the fact that stations with large asymptotic receiving cones and large penumbra effects can be effectively used in addition to stations having narrow receiving cones.

2.4. Some peculiarities of equipment for recording solar cosmic rays. The equipment used for recording solar particles is similar to the one for galactic cosmic rays. But the sporadic nature of flares, steeper spectrum of particles, the high intensity of solar particles and limitations on the duration of the event impose additional demands on the equipment which, firstly, should record the beginning of a flare with the maximum possible accuracy and secondly, should make it possible to get data about the intensity for any given interval of time during the event. Moreover, the programming of the apparatus from one operation schedule to another (namely in the beginning, it should record flares and afterwards, the undisturbed flux of cosmic rays) should be automatic.

Keeping in mind the above point, J. Simpson [52] has designed a special device which could differentiate the beginning of a flare in neutron monitor with an accuracy of 1 min and which could automatically take photographs every minute and later on, after every five minutes. This device helped in getting exceptionally valuable data during the February 23, 1956 flare.

Ya. L. Blokh [53] designed a similar device for telescope counters and, in this case, the photorecorder recorded the time and readings of the scaler after every 1-1/2 minutes.

In the case of ionization chamber, the electrometer goes out of scale due to a sudden increase in the intensity, and the instrument is no longer sensitive to the change in the intensity until the central electrode is not grounded again. After grounding, the recording continues for a few minutes after which the indicator again goes out of scale and the instrument does not operate for a long time till it is grounded once again. Hence the instrument does not operate during the most interesting periods of the increase in the intensity of cosmic rays. Because of this, Yu. G. Shafer [54] has redesigned the instrument making it possible to switch over the electrometer quadrants to be fed with low voltage immediately after the beginning of the sharp increase (i.e., before the indicator goes out of scale for the first time). It reduced the sensitivity of the electrometer and helped to record all the incoming information.

The equipment meant for stratospheric, satellite and rocket measurements of solar particles differs from the ground equipment in weight, dimensions and geometry. In particular, a specific direction of detectors is required for measuring the degree of anisotropy of solar particles in the interplanetary space. In addition, a special memory system for storing the observed data and a system for telemetering the same to the Earth is necessary.

3. SENSITIVITY OF SOLAR PARTICLES TO PHYSICAL CONDITIONS IN THE COSMIC SPACE

Theoretical investigations on solar cosmic rays acquired great impetus during the last decade along with the development of the experimental techniques and accumulation of observational data. In the light of modern experimental data and theoretical concepts, propagation of solar cosmic rays can be considered as a single, complicated process defined by the properties of the medium through which the particles move.

During its propagation from the source to the observation point, a solar particle experiences the influence of solar atmosphere and local magnetic fields on the Sun, interplanetary medium, interplanetary and geomagnetic fields and of the

Earth's atmosphere. As a result of this interaction, individual characteristics of the particles (viz. trajectory, energy and charge) as well as group properties of a large complex of particles (viz. energy spectrum, nuclear composition, and total flux) should change. We will consider in the following paragraphs the role of basic factors which can give rise to a change in the spectrum, composition and other characteristics of solar particles.

3.1. Nuclear reactions. As shown by V. L. Ginzburg and S. I. Syrovatskii [21], the composition of galactic cosmic rays observed at the Earth considerably differs from that at their sources. This difference is caused by the nuclear transformations due to interaction of cosmic rays with interstellar medium in the process of their propagation in the galaxy. In this case, the cosmic rays are significantly enriched with protons and light nuclei due to the dissociation of heavy nuclei. A similar situation also exists in the case of propagation of solar cosmic rays. Hence let us consider the role of nuclear interactions in the interplanetary space, solar corona and in the chromosphere individually [2].

The amount of matter covered by solar particles in the interplanetary space is considerably less than the mean free path of nuclear interaction even for the heaviest nuclei. As a matter of fact, since the time lag of particles is of the order of one day, the velocity $v \sim 10^{10}$ cm/sec and the density of the interplanetary medium $n \lesssim 10^3/\text{cm}^3$, the total amount of matter traversed by the particles is $\lesssim 10^8$ atom/cm^2 or $\sim 10^{-6}$ g/cm^2, that means the nuclear reactions in the interplanetary space can be neglected.

During the course of passage of accelerated particles in the solar corona with density $n \sim 10^8$ cm^{-3}, nuclear reactions will be significant only if the time of existence of particles in the corona is $\gtrsim 10$ days. Since the acceleration process lasts for $\lesssim 1$ hour, the nuclear reactions in the corona will be significant only in the presence of magnetic traps capable of retaining the particles for a long period (for many days). Such traps can most probably exist [2] but their life can hardly be more than 1 day. Nuclear reactions in traps having such a life will be significant only if the density of the medium is $10^9 - 10^{10}$ cm^{-3}, i.e., if the particles move in the lower corona and upper chromosphere.

If the particles move in the chromosphere having n $\sim$ 10^{12} cm^{-3}, their life with respect to nuclear reactions at v $\sim 10^{10}$ cm/sec will be $\sim 10^2$-10^3 sec which is comparable to the acceleration period.

If acceleration process for all the nuclei proceeds in a sufficiently dense medium and is valid for a long time, the nuclear composition may get sufficiently enriched with light elements. However, even in this case, a large amount of Li, Be, B nuclei should have been observed in solar cosmic rays which is contrary to the observation data.

Thus, it can be confirmed that the composition of solar cosmic rays can change (by enriching with lighter nuclei) if there are long-life magnetic traps in the corona or if the acceleration process mainly takes place in the chromosphere at high density regions.

Since the nuclear reactions in the interplanetary space can be neglected, the measurements made at the Earth will mainly give information about the composition of particles corresponding to the time of their exit from the solar atmosphere.

It may be assumed that some amount of unstable isotopes is formed during nuclear reactions in the solar atmosphere. The distribution of solar particles according to energy and charge is changed to some extent by a part of them undergoing dissociation with half-life periods comparable to diffusion characteristic time. However, at present, there is no reliable data on isotopic composition of solar particles (see Section 9.3)*.

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* *Recently B. M. Kuzhevskii [III.166] showed that flux of* Be^7 *nuclei from a solar flare in the interval* $\mathcal{E}_k$ *= 40-400 Mev/nucleon can be much more than the flux of* Be^9 *nuclei. In the interval 120-204 Mev/nucleon, intensity of* Be^7 *nuclei can go up to* 1.2×10^{-3} m^{-2}.sec^{-1} sterad^{-1}*. There is a possibility of an increase in the flux of radioactive isotope as compared to the stable flux for cobalt nuclei as well* ($Co^{56}/Co^{59} > 1$ *in the interval 5-30 Mev/nucleon). At 30-400 Mev/nucleon energy, flux of radioactive cobalt is a few percents of the flux of stable cobalt.*

The role of nuclear reactions in the Earth's atmosphere is well evident from the fact that cosmic rays, before reaching the Earth's surface, must pass through the layer of air which is approximately equivalent to 15 nuclear mean free paths. In this case, characteristics of solar cosmic rays at the boundary of the Earth's atmosphere are evaluated with the help of the method of correlation coefficients (see Section 2.1).

3.2. Ionization losses. Ionization losses for two nuclei of cosmic rays -- light (hydrogen, $Z = 1$) and heavy (iron, $Z = 26$) -- during their propagation through the interplanetary medium with concentration $n \sim 1 \text{ cm}^{-3}$ can be estimated with the help of known formulas.

In the case of propagation of a nonrelativistic particle with kinetic energy $\varepsilon_k = 100$ Mev, losses on excitation and ionization of atoms of the medium are 3.23×10^{-7} ev/sec and 9.45×10^{-4} ev/sec for proton and iron nucleus respectively. In the relativistic case ($\varepsilon_k = 10^{10}$ ev), the ionization losses are as expected slightly less: 2.26×10^{-7} ev/sec for hydrogen and 1.07×10^{-4} ev/sec for iron.

In an absolutely ionized medium with electron concentration n_e, the ionization losses in the nonrelativistic case ($\varepsilon_k = 100$ Mev) are 1.35×10^{-6} ev/sec for hydrogen and 6.1×10^{-3} ev/sec for iron whereas for the relativistic case, they are 6×10^{-7} ev/sec and 3.9×10^{-4} ev/sec respectively.

Thus, ionization losses of solar cosmic rays in the interplanetary medium during diffusion period ($\sim 10^3 - 10^4$ sec) can be neglected. Even an increase in the density of the medium by one or two orders does not change this conclusion significantly.

It should be noted that the particles may not be completely ionized in the process of their acceleration at the Sun since the lower the degree of ionization of an atom, the lesser will be the injection energy. However, in the process, when the energy accumulates at sufficiently dense regions, the atom will more and more get ionized. Thus, the degree of ionization of accelerated atoms will be determined by the specific nature of the acceleration mechanism and by the density of the substance of the medium in which the energy accumulates. As stated earlier, the degree of ionization should not practically change during propagation through the interplanetary space. Data on the degree of ionization of solar particles are of exceptional importance for understanding the acceleration mechanism. Till this time, there are no such data available. The most direct information about the degree of ionization of nuclei could be obtained with the help of artificial satellites and cosmic rockets. To this end, it is possible to make use of the geomagnetic field dividing the nuclei of effective charge Z^* according to their rigidity $R^* = RZ/Z^*$ beyond the limits of the atmosphere. Thus $Z^* = RZ/R^*$ where R^* is determined from the geomagnetic theory and, R and Z, from the measurements by balloons.

In regard to the problems already discussed in Sections 3.1 and 3.2, the results of measurements, obtained by Bryant et al. [55] on spectrum of solar protons with $\mathcal{E}_k \geqslant 2$ Mev with the help of satellites "Explorer - 12" and "Explorer-14" beyond the limits of the Earth's magnetosphere, are of great interest. According to [55], the emission spectra of solar particles for a large number of flare events (September 28, 1961; November 10, 1961 and December 23, 1962) are well described by a power function of kinetic energy right up to $\mathcal{E}_k \sim 1$ Mev. From this, it is concluded that the amount of matter traversed by protons after acceleration was less than the mean free path for absorption of a proton having $\mathcal{E}_k = 1$ Mev, i.e., 10^{-3} g/cm^2.

Information on the isotropic composition is very important for evaluating the amount of substance traversed by solar particles after acceleration. For example, let us suppose that accelerated α-particles cross a layer of substance (hydrogen) $\leqslant 0.2$ g/cm^2 and the cross section of formation of He^3 is equal to 50 millibarn. In this case, the ratio He^3/He^4 will be $< 6 \times 10^{-3}$. This value is about 2 orders less than the value 0.2 obtained experimentally by Schaeffer and Zahringer [56] with an accuracy up to the third place. Basing our computations on the lower limit of the experimental relation (~ 0.06), we get the amount of traversed substance $\sim 1.2 \times 10^{24}$ atom/cm^2, i.e., approximately 1 g/cm^2, and this result is contradictory to Biswas's observations [57]. As shown in [57], data obtained by Schaeffer and Zahringer [56] are unreliable. A similar situation is observed in the case of measurements on the abundance of deuterium and tritium [28, 29].

3.3. Collision of solar particles with magnetic clouds. The modern model of interplanetary medium assumes a dynamically changing, in space as well with time, picture of motion of irregularities of magnetic field ("magnetic clouds") from the Sun. Therefore, the particles, generated during chromospheric flares, must experience the effect of retardation or acceleration in the process of collisions depending upon the fact as to whether they obvertake the magnetic clouds or undergo cross collisions with them. In the case of a collision with a magnetic irregularity, the acceleration is caused by the induced electrical field $E = -1/c\,[uH]$ originating due to motion of the magnetic field, frozen in the medium, with a velocity u. This effect is the basis of the statistical model of Fermi acceleration [58].

Solar particles propagate in an expanding beam of magnetic irregularities. In the long run, it must lead to some decrease in the energy of particles since they mainly undergo overtaking collisions. This "reverse" statistical mechanism of Fermi was first studied by B. L. Ginzburg et al. [59]. L.I. Dorman's estimate of the effect of retardation [60] gives the change in the energy per collision as $\delta\varepsilon = -\varepsilon u \Lambda v/c^2 r$. A particle, reaching the Earth in a time t after the flare, on an average, undergoes collisions $\nu = vt/\Lambda$ and average loss of energy will be $\Delta\varepsilon = \delta\varepsilon\nu = \varepsilon v^2 u t/c^2 r$. By taking the average for volume $\tilde{r}$ in which diffusion takes place, we get $\Delta\varepsilon = 3\varepsilon v^2 u t/2c^2\tilde{r}$. Thus, the later the particle reaches the Earth, the more will be the loss of energy (at $ut \sim \tilde{r}$, the loss will be significant for particles of any energy). The average time of propagation of particles from the Sun to the Earth is $t \sim r_{♁}^2/6\varkappa$. From this, we get for the average loss of energy, $\overline{\Delta\varepsilon} = 3\varepsilon uvr_{♁}^2/4c^2\tilde{r}\Lambda$. If $\tilde{r} \sim r_{♁}$, then $\overline{\Delta\varepsilon} \approx -uvr_{♁}/c^2\Lambda$. For high-energy particles $v \sim c$ and since $ur_{♁}/c\Lambda \ll 1$, the decrease in the energy of particles can be neglected deliberately. But if the particles are nonrelativistic, then $\varepsilon \approx m_0c^2$ and $\Delta\varepsilon/\varepsilon_k \approx 2ur_{♁}/v\Lambda$. If $u = 3 \times 10^7$ cm/sec and $v \approx 10^{10}$ cm/sec, then $\Delta\varepsilon/\varepsilon_k \approx 0$ at $\Lambda = 10^{12}$ cm, i.e., for the given case, at $\varkappa = 3 \times 10^{21}$ cm^2/

sec. Thus, the braking is noticeable only in the case of extremly low-energy particles and it leads to a change in the gradient of spectrum in the region of low energies. On the other hand, if the spectrum at low energies is plane, the retardation must partially compensate for the decrease in the intensity of particles caused by convection in the solar wind.

3.4 Effect of drift. According to Parker [61], the drifting velocity of a proton, having a kinetic energy $\mathcal{X}$ (in static-energy units) and moving perpendicular to an irregular magnetic field of intensity H $\sim 10^{-4}$ gauss and characteristic dimension L $\sim 10^{13}$ cm, is $u_{dr} = 4.5 \times 10^7 \times \mathcal{X} (\mathcal{X} + 2)/(\mathcal{X} + 1)$ cm/sec. During 5-hours of drifting, a proton with $\mathcal{E}_k = 10^{19}$ ev $(\mathcal{X} \approx 1)$ covers a distance of 1.2×10^{12} cm = 0.09 a.u. During the same period, a proton with $\mathcal{E}_k = 10^8$ ev covers a distance which is eight times less whereas a proton with $\mathcal{E}_k = 10^{10}$ ev covers about seven times more distance. From the above it is obvious that firstly, the particles fill the interplanetary space quickly due to drift only at the highest values of $\mathcal{E}_k \approx 10^{10}$ ev and reach the Earth in accordance with the observed time lag of the order of a few hours; secondly, in the process of drifting the beams of high-energy and low-energy particles get absolutely separated and this is contrary to the observations on particles with $\mathcal{E}_k \lesssim 10^9$ ev. Hence, it is difficult to formulate such a theory of propagation of solar particles which may be based on the drifting of particles. In all probability, drifting of particles does take place and plays some role in the large-scale interplanetary fields but this effect does not play the leading role, most probably, excepting in the case of particles with extremely high energies. Of course, this preliminary conclusion does not settle the problem of the role of drifting in propagation of solar particles. In this connection, it is pertinent to point out that the drifting velocity of an α-particle having the same magnetic rigidity as a proton of energy $\mathcal{X}$ is less than that for the proton by nearly $[1 - 3/4(\mathcal{X} + 1)^{1/2}]$. The Larmor radius and the drifting velocity of an α-particle having the same energy per nucleon are twice than those of a proton.

If there is a large number of inhomogenities in the interplanetary space, then, the term that is more important in the equation for diffusion coefficient is not the velocity of the particles but the drifting velocity in the inhomogeneous regions of the magnetic field (if the irregularities completely fill the space) or in other words, the average effective velocity of particles obtained by considering the effect of drift (if the irregularities of the field are at an average distance of d from each other) [2].

In principle, additional migration of particles due to convection from the Sun to the Earth is possible due to the directed radial motion of magnetic irregularities (see Chapter IV)*.

3.5. Acceleration of solar particles in the interplanetary space. Interesting effects due to the increase in the flux of solar particles before the sudden commencement of geomagnetic storm were noticed by Axford and Reid [62] on the basis of cosmic radio noise absorption records during the polar cap absorption events of February 11, 1958, May 8, 1960 and September 30, 1961. Simultaneous measurements on satellites "Explorer-12" and "Injun-1" during the September 30, 1961 event, also confirmed the assumption that the increase in absorption was caused by the increase in the flux of low-energy solar protons. The increase in absorption before the commencement of magnetic storm is interpreted [62] on the basis of "compression" of particles between two shock waves in the interplanetary medium. One of these shock waves responsible for the geomagnetic storm moves from the Sun to the Earth at a velocity ~1000 km/sec. The second "standing" wave is caused by the moving solar wind interacting with the Earth's magnetosphere.

As a result of the "compression", the particles accumulate in-between the waves and their energy increases owing to Fermi's acceleration mechanism. Both these effects, acting simultaneously, give rise to an increase in the flux of particles whose energy is higher than the energy near the Earth's surroundings. As shown in [62], most of the peculiarities observed on cosmic radio noise absorption can be explained on the basis of the above interpretation.

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[*] *As pointed out by Parker [61], the convection of particles in the solar wind, just like the negligibly small large-scale drift (these effects are comparable with respect to order of magnitude), mainly serves for migration and expansion of particle distribution caused by disorderly movement (diffusion). This movement is more complicated than the convection process and in most of the cases, takes place at a higher speed.*

3.6. Solar cosmic rays and local cut-off rigidities in the geomagnetic field. As pointed out by Ray [63], measurements on spectra of solar protons at northern latitudes showed that the cut-off rigidity in this region, even during magnetically quiet days, is, in general, considerably less than that obtained by calculations in which the actual distribution of geomagnetic field obtained from ground data, and the corresponding ring current are taken into account. According to Ray [63], many of the descrepencies can be easily explained by considering, in addition to the above-mentioned components of the field, another turbulent component existing at all places beyond a certain distance from the center of the Earth.

Similar studies are also made by Akasofu et al. [64]. They, in addition to the differences between effective and calculated rigidities during magnetically quiet days, estimated the effect of the decrease in cut-off rigidity during the main phase of the magnetic storm mentioned by Winckler et al. [65]. Both the effects are considered within the framework of present concepts about the ring current which is caused by the particles captured in the geomagnetic field, and about the magnetosphere extending up to a distance of 8-12 earth radii (r_E) and is in conformity with the data obtained by Satellites "Explorer-12" and "Explorer-14". The effect of compression of magnetosphere is shown in Fig. 3.1. The prohibited (dark) and permissible (bright) zones in the spherical magnetosphere are shown for particles with kinetic energies equal to 500 kev, 1 Mev, 30 Mev and 100 Mev.

Kellog and Winckler [66] pointed out, that the ring current leads to a decrease in the cut-off rigidity at a given point at high altitudes by a factor $k = 1/(1 + M_R/M_E)$ where $M_E = 8.1 \times 10^{25}$ gauss. cm^3 is the magnetic moment of the Earth and M_R is the magnetic moment of the ring current. Calculations show that the ratio M_R/M_E cannot be more than one. It is evident from this that only the ring current cannot reduce the rigidity R by a factor < 0.5. The observed value of k are of the order of 0.2 which corresponds to the extremely large value $M_R/M_E = 4$. In practice, still lower values of k are observed. According to observations of Maehlum and O'Brien [67] on July 12, 1961 (magnetically calm period) at College (Alaska) where usually protons with $\mathcal{E}_k \gtrsim 15$ Mev ($R = 0.168$ Gv) reach during magnetically calm days, protons

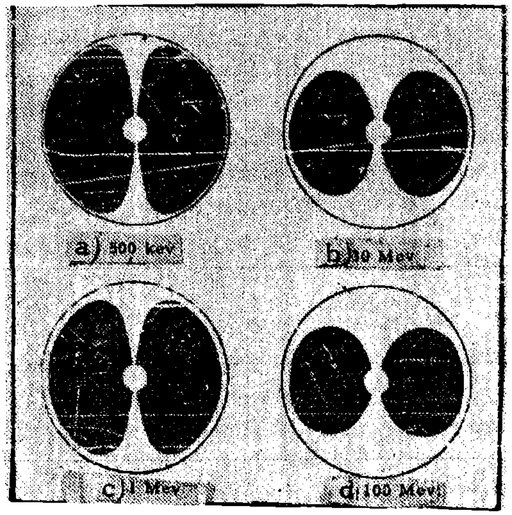

Fig. 3.1. Prohibited (dark) and permissible (bright) zones in the Earth's magnetosphere for particles having kinetic energies equal to 500 kev (a), 1 Mev (b), 30 Mev (c) and 100 Mev (d).

with $\mathcal{E}_k \sim 1$ Mev ($R = 0.0433$ Gv) started arriving during the main phase of magnetic storm. It corresponds to a value of $k = 0.09$ or $M_R/M_E = 10$ which is absolutely impossible. A similar study of the second possibility showed that the observed decrease in rigidity cannot be completely explained only with the help of compression of magnetosphere which reduces the angle between the dipole axis and the lines of force near the poles and thus, facilitates penetration of low-energy particles. Under certain simplified assumptions (particularly in the case of vertically falling particles), Akasofu et al. [64] showed that the observed decrease in rigidity can be quantitatively explained by a suitable combination of both the disturbing processes.

In connection with the problem under reference, Stone's work [68] is of great interest. In this work, the dependence of cut-off rigidity on local time has been investigated for protons with $\mathcal{E}_k = 1.5$ Mev. The investigation was conducted with the help of satellite "Discoverer-36" launched on September

17, 1961 into the solar orbit having the following parameters: apogee height 396 km, perigee height 235 km, angle of inclination of the orbit to the plane of equator 82.7°. Low-energy protons along the orbit of the satellite during the period of low geomagnetic activity were measured with the help of telescope counters having solid scintillators and installed in vertical and horizontal directions. At all latitudes higher than the characteristic cut-off latitude for these protons, a low flux of protons with $\mathcal{E}_k = 1.5$ Mev was observed which interacted with the geomagnetic field as individual particles. The observed vertical cut-off corresponded to geomagnetic latitude of 65° on the nocturnal side and 67° on the diurnal side whereas the theoretical Stormer cut-off should be observed at a latitude of 76°. The dependence on local time was also observed for the so-called transition width characterized by the difference in the latitude at which the flux becomes measurable for the first time and the latitude at which the maximum (plateau) of flux is observed for the first time. On the nocturnal side, the transition width was 1° and on the diurnal side, it was $\sim 3°$ and is found to be variable. Horizontal cut-off latitudes were approximately the same. Essentially identical results were obtained for both the north and the south poles. These results show that polar regions were absolutely accessible to protons with $\mathcal{E}_k \approx 1.5$ Mev. The obtained results do not predict any of the existing theories of geomagnetic cut-off and must be considered in the light-of computations on proton beams which give rise to polar cap absorption of radio waves.

Stone's measurements [68] are of special importance since the equipment meant for measuring the absorption of radio waves cannot accurately define the boundary of the region of polar cap (geomagnetic latitude $\gtrsim 65°$) from the side of low latitudes.

Hakura [69] studied similar problems. It is pointed out that the observed cut-off rigidities of cosmic rays in polar regions are considerably less than those expected from Störmer's theory even during magnetically calm periods. The latitudinal dependence of non-störmer cut-off rigidities is determined on the basis of the data on polar absorptions and observations on subcosmic radiation made with the help of balloons and satellites. It was shown that cut-off rigidites in the latitude range of 55-65° differ from the dipole rigidities by a factor of about 0.7. Below 55°, the rigidities change to a lesser extent and are approximately equal to dipole rigidities. This can be explained on the basis of the assumption regarding ring current in the calm field.

Satellite observations on solar particles show that the cut-off disappears in the polar cap at a latitude $> 65^{\circ}$. Theoretical models of asymmetrically deformed magnetosphere suggested by Michel and Dessler [70], Dangey [71] and Levy et al. [72] obviously satisfactorily explain the abnormal invasion of low-energy particles in polar caps although these models considerably differ from each other in the estimation of the role of interplanetary and geomagnetic fields and the resultant interval of time required for invasion of particles in the magnetosphere.

Polar cap absorption events can be utilized for confirming these theoretical models since these effects testify to the transient nature of invasion of solar particles in the upper atmosphere. It is clear that the initial absorption phase consists of at least three characteristic stages which proceed successively in different zones of polar regions. The transition period from first stage to the second is usually of the order of a few hours which testifies to the absence of a direct relation between geomagnetic and interplanetary fields.

Hakura [73] considered the role of solar α -particles in increasing the ionization at the boundary of the region of polar absorptions.

Geomagnetic coordinates corrected by considering higher harmonics of dipolar expansion are used for analyzing polar absorptions. The analysis shows that figures -- oval in shape in the coordinate system of centered dipole -- of well-developed polar absorptions get circular shape in the corrected system and as such, provide unified cut-off latitudes for solar particles giving rise to polar absorptions.

In the corrected system, the minimum cut-off latitudes changed from event to event within the limits of 65-54°. Threshold rigidities of particles, capable of giving rise to polar absorptions, were calculated in [74] for the case of protons and α-particles. The maximum of the obtained values, known as total threshold rigidity, can be related to the latitude cut-off of polar absorptions.

Using rigidity spectra of solar particles suggested by Freier and Webber [III. 6], it is possible to draw the conclusion from statistical considerations that in most of those flares of solar cosmic rays when the ratio $\alpha/p \sim 1$, well-formed equatorial boundaries of absorptions are caused by α-particles. Therefore, the term "flare of solar protons" as applicable to polar absorptions should be corrected.

There are some exceptions in the case of "purely proton flares" when the flux of α -particles is insufficient for causing the absorption. The limit of minimum latitudes in these cases was usually grouped around 65° in the corrected system.

Reid and Sauer [74] studied the relation between the polar absorptions and the tail of the Earth's magnetosphere. It can be reasonably expected that the geomagnetic tail will have an effect on the cut-off rigidities of low-energy solar protons (1-100 Mev) and therefore, on the global distribution of polar absorptions. If the tail is very long, excess flux of protons will invade the polar regions and, according to the model of Michel and Dessler [70], rigidities different from zero will be observed at high latitudes. On the other hand, rigidity in subpolar regions will come down to values considerably lower than those expected in the absence of the tail. The simple model [70] for determining the effect of tail on cut-off rigidities in subpolar regions is well in line with the available observation data.

Williams and Boström [75] studied the results of observations on solar protons during February 5, 1965 flare event. Measurements were made with the help of high-latitude satellites "1963-38-C" and "Injun-4" with low orbits. According to observations [75], low-energy protons ($\mathcal{E}_k \sim 1$ Mev) have time variation which is not in conformity with the diffusion of particles and is characterized by a series of fluctuations in the intensity. These observations in the polar cap are compared to the time variation of protons having similar energy on the basis of observation by "Mariner-4" up to 3000 r_E in the antisolar direction. The comparison shows that most of the lines of force of the geomagnetic field are closed up to the arrival of plasma cloud from the flare; after the solar plasma reaches the Earth, a long magnetic tail in which most of the lines of force are not closed is formed.

The difference in the times of arrival of these protons at "Mariner-4" and to the region of the polar cap is discussed by assuming different shapes of the magnetosphere. In particular, the arrival of low-energy protons to "Mariner-4" about 4 hours before they are observed at the polar cap is in line with the assumption regarding the extent of the magnetospheric tail. In general, the obtained data cannot be interpreted in a unique way on the basis of such a model. Even then, the comparison of time variations of low-energy protons in the polar cap and at a distance of about 3000 r_E in the antisolar direction shows that considerable changes were observed in the shape of Earth's magnetosphere during February 5, 1965 flare event.

On the basis of Taylor-Hones model [77] of geomagnetic field, Taylor [76] recently carried out numerical machine-computations on the trajectories of protons with $\mathcal{E}_k = 1.2$ Mev passing through infinity. Only those particles were taken into account which attained a height $\lesssim 2000$ km from the Earth's surface. For these particles, calculations show that: (a) the lines of force reaching the Earth at latitudes less than 65^o are inaccessible to particles with pitch angles $\theta = 0$-90^o irrespective of the local time; (b) the lines of force in the latitude range of 65-75^o on the diurnal side of the Earth are accessible only to particles with high pitch angles at a height $\sim$ 2000 km (i.e., moving approximately orthogonally to the vector of magnetic field); (c) the "polar plateau" -- cloud of inaccurate shape obviously accessible to protons with any pitch angles between 0 and 90^o -- extends from the pole to 65^o at the midnight meridian, to $\sim 75^o$ at the noon and morning meridians and to $\sim 70^o$ at the evening meridian. A comparison with the observations of Stone [68] and Harding et al. [III. 101] confirms the accuracy of the calculations [76].

3.7 Shock zones for solar particles in the geomagnetic field. The analysis of the increase in the intensity of cosmic rays shows that the beam of solar particles is anisotropic at least at the initial stage. The radiation propagates from the Sun within a limited solid angle and the distribution of intensity on the Earth's surface is mainly determined by the spectrum of particles in the beam and by the effect of geomagnetic field on it. As shown by Firor [7], trajectories of solar particles with $\mathcal{E} \sim 0.03$-10 Gev tend to group themselves in the geomagnetic field into isolated families and form the so-called shock zones.

Formation of three well-defined zones -- at 0900 hours (centering at about 0900 hours local time), 0400 and 2200 hours- is of special importance. In addition, there is the fourth background zone which at R = 0.03-10 Gv covers whole of the region in the latitude range of 28-78°. Firor's calculations [7] show that the ratio of intensities in the basic shock zones in the case of a plane spectrum is 7:3:1. However, subsequent and more accurate calculations of Lüst [78] and Sakurai [79] which take into account the sharply-falling nature of the spectrum, point out a more complicated picture of the distribution of intensity of solar cosmic rays in the shock zones. In particular, it becomes apparent that in some cases, at medium geomagnetic latitudes, the intensity of the flare radiation is maximum in 20-hour shock zone. There can also be cases when intensities of all the three zones are comparable among themselves. It should be pointed out that these results refer to the intensity at the boundary of the atmosphere. On the other hand, the sensitivity of the recording equipment varies for different regions of the spectrum, and also the energy of the particle decreases during the transition from 9-hour zone to the background zone at the given geomagnetic latitude. If these above facts are taken into consideration, the actual distribution of intensity at the surface of the Earth may considerably differ from the one calculated by Firor [7]. Noncoincidence of the axis of the Earth's rotation with the axis of geomagnetic dipole gives rise to diurnal and seasonal changes in the position of shock zones [2].

3.8. Transformation of energy spectrum and nuclear composition of solar particles in the process of diffusion.

The effect of the interplanetary medium on the propagation of solar particles from the Sun to the Earth is not limited by the above-mentioned phenomena. Investigations conducted during the past 10 years showed that the interplanetary magnetic fields play a leading role in the propagation of solar particles. Different models of propagation of solar particles are considered in Chapter IV. The most significant consequence of diffusion of solar particles at irregularities of the interplanetary field is the change in their energy spectrum and nuclear composition with the passage of time.

As a matter of fact, it was observed by Pfotzer [45] that even during the February 23, 1956 flare event, the differential spectrum of pulses in the region $2.5 \leqslant p \leqslant 6.0$ Gev/C is of the type $p^{-3.4}$ for particles coming directly from the Sun whereas the spectrum of scattered particles was much steeper (p^{-6} or p^{-7}), i.e., the beam of scattered particles was enriched with low-energy particles. Sharply-defined dispersion effect (i.e., delay of low-energy particles) was observed during the flare events of September 3, 1960 (Bhavsar [80] and Davis et al. [81]), November 12, 1960 (Lockwood and Shea [82]), September 28, 1961 (Bryant et al. [23]) and in many other cases.

These experimental observations are naturally explained by the assumption that the diffusion coefficient increases significantly due to an increase in the energy (rigidity) of the particles. As shown in Section 13, the mean free path for scattering is determined by the rigidity of particles $R = cp/Ze$ and depends on the distribution of magnetic irregularities and intensity of their field in space. It follows from this that the diffusion coefficient of particles $\varkappa = \Lambda v/3$ can depend on the rigidity of particles as well as on their velocity. This dependence is especially significant in the region of nonrelativistic energies where, in contrast to relativistic case ($\varkappa \sim \Lambda$ since $v \sim c$), the additional dependence on the velocity $\varkappa \sim v$ will also have an effect. This fact has a significant effect on the time of propagation of particles from the Sun to the Earth (since $t_{max} \sim \varkappa^{-1} \sim v^{-1}$). Moreover, nuclear composition of solar cosmic rays should change with time due to this very reason. As a matter of fact, the velocity of nuclei in the nonrelativistic region is less than the velocity of protons at the same magnetic rigidity by approximately two times since the ratio of charge to the mass number Z/A for all the nuclei with $Z \geqslant 2$, detected in solar cosmic rays, is of the order of $1/2$. Two important conclusions can be drawn from this. Firstly, separation of beams of protons and heavier nuclei of the same rigidity (enrichment of the beam of solar particles with nuclei having $Z \geqslant 2$ at large t) must be observed during cosmic ray flares. Secondly, all the nuclei with $Z \geqslant 2$ at a constant value of R should be simultaneously present in the beam of solar cosmic rays, i.e., there should not be any further separation of the beams of nuclei according to Z. Some simple relations (Hakura [83]) are cited as an illustration.

If the spectrum of solar particles according to their rigidities at the time of emission was of the type $D_s(R) = D_{os} \exp(-R/R_{os})$, then, as a result of diffusion, during observations at the Earth's orbit, we get

$$D_p(t, r_{\text{♁}}, R) = \frac{D_{0s}\exp(-R/R_{0s})}{(2\sqrt{\pi\varkappa_p t})^3}\exp\left(-\frac{r_{\text{♁}}^2}{4\varkappa_p t}\right). \qquad (3.1)$$

$$D_a(t, r_{\text{♁}}, R) = K_s\frac{D_{0s}\exp(-R/R_{0s})}{(2\sqrt{\pi\varkappa_a t})^3}\exp\left(-\frac{r_{\text{♁}}^2}{4\varkappa_a t}\right) \qquad (3.2)$$

for protons and α-particles respectively where K_s is the ratio of α-particles to protons in the source. On the other hand, according to Freier and Webber [III.6], the spectrum observed near the Earth is of the type

$$D_p(t, r_{\text{♁}}, R) = D_0(t)\exp\left(-\frac{R}{R_0(t)}\right), \qquad (3.3)$$

$$D_a(t, r_{\text{♁}}, R) = K_{\text{♁}}(t)D_0(t)\exp\left(-\frac{R}{R_0(t)}\right) \qquad (3.4)$$

for protons and a-particles respectively where $K_{\text{♁}}(t)$ is the ratio of a-particles to protons at the Earth's orbit. Taking into account the fact that the flux of particles during diffusion is maximum at $t_m = r_{\text{♁}}^2/6\varkappa$ from (3.1)-(3.4) we get

$$K_{\text{♁}} = \left(\frac{\varkappa_p}{\varkappa_a}\right)^{3/2}\exp\left[-\frac{r_{\text{♁}}^2}{4t}\left(\frac{1}{\varkappa_a}-\frac{1}{\varkappa_p}\right)\right]K_s =$$

$$= \left(\frac{t_{ma}}{t_{mp}}\right)^{3/2}\exp\left(-\frac{3}{2}\frac{t_{ma}-t_{mp}}{t}\right)K_s. \qquad (3.5)$$

If the protons are emitted with the same rigidity, then $v = a_{vp}$ where $a = 1/2\,[\sqrt{1-3/4(v_p/c)}]^{-1}$, i.e., $1/2 < a < 1$. Since in the nonrelativistic case, velocity of protons $v_p \approx 2v_a$, (3.5) becomes

$$K_{\text{♁}}(t) = 2^{3/2}\exp\left(-\frac{3}{4}\frac{t_{ma}}{t}\right)\cdot K_s \qquad (3.6)$$

or

$$\frac{K_{\text{♁}}(t)}{K_s} = 2^{3/2}\exp\left(-\frac{0{,}75}{\tau}\right), \qquad (3.7)$$

where $\tau = t/t_{m\alpha}$. The relations (3.6) and (3.7) are also applicable to integral spectrum of rigidities.

Thus, by measuring the time of maximum for beams of nonrelativistic protons and α -particles near the Earth, it is possible to calculate their ratio $K_{\frac{t}{\delta}}$ (t) at constant rigidity for any moment of time with an accuracy factor of K_s which characterizes the process of acceleration of particles at the source.

In the relativistic region, the ratio of the flux of protons to that of nuclei with $Z \geqslant 2$ at any moment of time should essentially be the same as that at the time of their emission from the source. Unfortunately, experimental data in this direction are extremely scanty. For example, on the basis of the data of stratospheric measurements conducted by Biswas et al. [84] during September 3, 1960 flare, it is observed that the beam of α-particles has a tendency to get enriched with low-energy particles with the passage of time. A more definite result was obtained in the work of Biswas et al. [24] for November 12, 1960 flare. According to [24], the differential spectrum of solar particles for energies $\mathcal{E}_k > 35$ Mev/nucleon had the form of a power function and the index was the same for α--particles and medium nuclei but was about twice the index for protons in the energy range of 40-130 Mev/nucleon. This difference is explained by the dependence of diffusion coefficient on the energy of the particles.

By comparing the results of September 3 and November 15, 1960 flares, Ney and Stein [85] showed that the ratio of protons to α -particles or to medium nuclei can change considerably (by more than an order) from case to case whereas the ratio of the flux of α -particles to that of heavy nuclei practically remains constant.

It should be pointed out the relations mentioned here are applicable only to isotropic diffusion in inorganic medium. The effect of properties of the source, geometry of diffusion process, structure and dynamics of inteplanetary medium on the energy spectrum of solar particles is analyzed in Sections 14 and 15.

In the end, before this Chapter is concluded, let us mention some of the review works on generation, propagation and techniques of detection of solar particles: L.I. Dorman and L.V. Raichenko [86], Obayashi [87], Parker [88], Webber

[89], Roederer [90, 91], Lüst [92], Sakurai [93], A. N. Charakhch'yan and T. N. Charakhch'yan [94], Anderson [95], Pfotzer [96], Pieper et al. [97].

Supplement to Section 3.6. At the International Conference on Cosmic Rays held at Calgary, Canada in June, 1967, R. Gall and J. Jiminer reported the results of machine computations of 150 trajectories of protons with energy from 1 to 500 Mev in the geomagnetic field. A model of magnetosphere suggested by Williams and Mead (D. J. Williams, Mead G. D., J. Geophys. Res., 1965, 70, No. 13, 3017) was used in the calculation which was done with the aim of determining the cut-off rigidity for Kiruna station at midnight. According to calculations, the geomagnetic threshold at Kiruna is 47 Mev for the model of central dipole, 104 Mev for eccentric dipole and 135 Mev for actual dipole by considering the first six harmonics of dipole expansion. On the other hand, calculations done by Gall and Jiminer on the basis of the model of Williams and Mead gave considerably lower values: 4 ± 1 Mev at night and 47 ± 2 Mev during day. Gall and Jiminer assumed that particles enter the magnetospheric tail at a distance of 25 r_E and afterwards, channelize in the tail in a complicated manner. The value of the geomagnetic threshold at night $g_n = 4 \pm 1$ Mev is obtained by assuming that the intensity of magnetic field in the tail being $H_t = 40\gamma$. The threshold value considerably depends on H_t. For instance, $g_n = 22 \pm 2$ Mev at $H_t = 15\gamma$. Coordinates of the regions of the entry of protons of different energies, reaching Kiruna along the vertical at noon and midnight at $H_t = 40\gamma$, are given in the work of Gall and Jiminer. Asymptotic directions of particles reaching Kiruna also depend on the local time. The obtained results for geomagnetic cut-off rigidities conform better to the approximate estimates [74] than to the model of dipole field.

Thus, direct calculations of trajectories of particles show that consideration of the effect of the tail of magnetosphere actually helps in understanding many peculiarities of the behavior of low-energy cosmic rays (including those of solar origin) at high latitudes.

CHAPTER II

GEOPHYSICAL EFFECTS OF SOLAR COSMIC RAYS

The invasion of solar cosmic rays in magnetosphere and in the Earth's atmosphere is accompanied by a number of geophysical phenomena which are considered below.

4. SOLAR COSMIC RAYS AND RADIATION BELTS OF THE EARTH

Solar cosmic rays can play a role in the Earth's radiation belts by the following three possible processes: 1) capture of solar particles of the lowest energy in the magnetic trap near the Earth; 2) formation of neutrons due to nuclear reactions of solar particles in the Earth's atmosphere followed by dissociation $n \to p + e^- + \tilde{\gamma}$; 3) emission of neutrons during chromospheric flares with subsequent dissociation $n \to p + e^- + \tilde{\gamma}$ in the interplanetary space.

Let us consider some of the experimental data.

Gauger [1] reported the results of measurements, taken in 1962, on neutron flux in atmosphere at depths 160-300 g/cm^2 in the latitude range up to 55°N. It was shown that the spectrum in the region of $\mathcal{E}_k > 60$ Mev was steeper than the one observed in 1959 whereas the spectrum did not practically change in the energy interval 10 Mev $\leq \mathcal{E}_k \leq$ 60 Mev. An increase in the flux of neutrons with $\mathcal{E}_k > 60$ Mev was observed on July 21, 1962 in the latitude range of 50-55°N which is related to the possible pouring out of protons temporarily captured in the region between inner and outer radiation belts.

Katz et al. [2] studied the effect of a solar flare on the outer radiation belt of the Earth. Scintillation spectrometers for recording flux of electrons with $\mathcal{E}_k = 0.7$-4 Mev and protons with $\mathcal{E}_k = 1$-4 Mev were installed on the satellite "Hitch-hiker-1".

Data on the effect due to a solar flare, observed at 0734 UT on July 4, 1963, on the outer radiation belt was discussed in the work [2]. In particular, it was observed that at $L = 5$ and $\lambda = 55^{\circ}$, the flux of electrons in the belt decreased by more than an order and that of protons by about three times whereas their spectra and distribution according to pitch angles practically did not change. Restoration-time constant for the flux of electrons was approximately equal to 2 days. If the mechanism of loss processes remains unchanged and if the influx of electrons with energies $\mathcal{E}_k > 1$ Mev from the source is also constant, then its power should be $\sim 10^{13}$ erg/sec. Protons are restored at a rate slightly less than that for electrons. Disturbances in the inner belt ($L < 3$) were not observed.

On the basis of the data on measurements of protons by the satellite "Injun-1", Zmuda et al. [30] showed that the inner radiation belt practically did not change at the time of arrival of solar protons and during the magnetic storm (September 28, 1961-October 4, 1961).

During July 7, 1966 flare event, Krimigis et al. [89] conducted simultaneous observations on protons with energies 0.503-4.2 Mev inside and outside the magnetosphere with the help of satellites "Injun-4" and "IMP-1" ("Explorer-33") respectively. It was shown that solar protons of this energy propagate from interplanetary space to polar regions of the Earth very quickly (with a delay $\lesssim 0.5$ hour). This quick penetration is most probably caused by the anomalous diffusion of particles in the tail of the magnetosphere through the geomagnetic field.

The possible contribution of the particles, which are produced as a result of solar neutrons, to radiation belts is considered in Section 23.

Dragt et al. [4] estimated the relative contribution of albedo neutrons, formed by galactic cosmic rays and solar protons, to radiation belts. The important results obtained in the work [4] lead to the following conclusions. 1) The flux of protons with $\mathcal{E}_k > 20$ Mev in the radiation belts can be explained by nuclear reactions of galactic particles in the Earth's atmosphere only if the flux of the neutrons were 50 times the value used in [4]. In this case, in order to describe the distribution of protons along the lines of force of the geomagnetic field, it is necessary to consider scattering by magnetohydrodynamic waves beyond the limits of the ionosphere in addition to the atmospheric scattering. 2) The relative role of solar protons in the same range of energies is small. 3) At $\mathcal{E}_k < 20$ Mev, the amount of protons in the radiation belts is extremely large so that it may be explained by the disintegration of neutrons and therefore, it is necessary to consider other sources.

The results of calculations of the intensity, spectrum and the angular distribution of neutrons produced by solar protons in the Earth's atmosphere are referred to in the works of Lingenfelter and Flamm [5, 6]. Calculations were made for protons with $\mathcal{E}_k < 10$ Mev for different solar flare events and also for integral neutron flux during the whole of the last solar activity cycle. The spectrum of solar protons was assumed to be of the form $dI/dR = (dI/dR)_0 e^{-R/R_0}$ values of R_0 and $(dI/dR)_0$, averaged for the cycle were found to be 125 Mv and 2 proton. cm^{-2}. sec^{-1}. Mv^{-1} respectively. The angular distribution is approximately described by the dependence of $\sim \cos^2\theta$ in the case of slow neutrons, it is isotropic at intermediate energies and has a maximum at large values of θ in the case of high energies (θ is the angle relative to the direction of a falling proton). The fluxes of albedo and stable neutrons calculated as a function of characteristic rigidity R_0 and geomagnetic cut-off rigidity, are in agreement with the available observations within the limits of experimental errors.

5. EFFECT OF SOLAR COSMIC RAYS ON ATMOSPHERE

5.1 Absorption of short radio waves. Many indirect methods have been developed recently for the measurement of solar cosmic rays. These methods mainly involve the observation of the following effects caused by the interaction of these particles in the Earth's ionosphere: (1) absorption of cosmic radio. noises; (2) scattering of short radio waves; (3) observation of minimum reflection frequencies f_{min}; (4) vertical sounding of the ionosphere; (5) propagation of short radio waves from satellites and spaceships to the Earth; (6) diffusion aurora in polar caps; (7) effect of γ-rays in the atmosphere, etc.

It may be appropriate to mention in this connection that the existence of a close relationship between ionosphere phenomena and solar cosmic rays prompted many research workers to have a close look again of the available geophysical data of earlier years. In particular, on the basis of a study made with the data on the propagation of radio waves and the results of cosmic rays recorded by shielded ionization chamber at Cheltenham, Zirckler [7] arrived at the conclusion that cosmic rays generated by the chromospheric flare of September 9, 1937 reached the Earth between 1200-1230 UT.

From a study of the data on the vertical sounding of the ionosphere at high-latitude stations before 1956, Swestka [90] detected 47 most probable cases of polar cap absorption events during 1938-55. The comparison of the vertical incidence recordings with those of the absorption effects during the period 1956-59 resulted in a uniform and complex distribution events during the whole separation of strong absorption events during the whole period 1938-63. On the basis of the above results, absorption effects are predicted - about 10 in 1966 and 25 in 1967-68. Moreover, 30% of these phenomena must be strong.

Interesting riometric data at 30 MHz were obtained by Goedke and Masley [8] in 1962-63 at McMurdo (Antarctica). Two cases of confirmed absorption event in the polar cap were noticed in 1962. The first absorption started at 0700 UT on February 22, 1962; it continued for almost the whole of the next day attaining maximum of ~ 0.7 db at 1600 UT and ending at 2300 UT. This event was also recorded at high northern latitudes (in particular, at Thule, Greenland). Simultaneously, magnetic storm was observed with a sudden commencement at 0220 UT on February 22, 1962. It was supposed that these effects were caused by two or three class 2 flares which were observed at the eastern limb of the Sun between 1200 and 2200 UT on February 19, 1962. During the period from 1500 UT on February 20, 1962 and ending at 2100 UT on the next day, Zmuda et al. [3] recorded the solar protons having flux intensity $I \sim 70\text{-}100$ cm^{-2}, sec^{-1}, sterad^{-1} in the energy range $1 \leqslant \mathcal{E}_k \leqslant 15$ Mev with the help of the satellite "Injun-1". The second case of absorption in 1962 was caused by the flare of class 2 with heliocoordinates 02°N, 71°W recorded at 1645 UT on October 23, 1962. In this case, radio emission of type IV was observed between 1656 and 1813 UT. The time difference between the start of the chromospheric flare and the beginning of the absorption was of the order of 45 minutes. The absorption started at 1730 UT on October 23, 1962, attained a maximum of ~ 1.1 db at about 0020 UT and ended at 1000 UT the next day. The intensity of protons in the energy range $\mathcal{E}_k$ = 0.5 - 10 Mev and 400 particles cm^{-2} sec^{-1} sterad^{-1}. Simultaneously, an increase in the intensity of protons in the interplanetary space was observed by Van Allen et al. [9] on "Mariner-2" and by Bryant et al. [1.23] on "Explorer-12". The absorption of ~ 0.6 db on February 9, 1963 also coincided with the sudden commencement of the geomagnetic storm. This event is most probably related to a class 2 flare that occurred at 2219 UT on February 6, 1963 with heliocoordinates 17°S, 08°W. Solar protons were observed on the satellite "Alouette" simultaneously with the absorption of radio waves. A similar case was observed on April 15, 1963 with an amplitude ~ 0.9 db and the equipment on "Injun-1" satellite recorded at the same time an increase in the flux of solar cosmic rays.

In September 1963, Masley et al. [10] measured polar absorptions at magnetoconjugate points, McMurdo (Antarctica) and Shepherd (Canada) using two identical riometers at 30 MHz. These stations are situated within the limits of polar caps and are both displaced towards geomagnetic poles with respect to the zones of polar aurora which provided reliable recording on propagation of solar particles. On September 10, 1963, the central meridian of the Sun was traversed by the active region which was responsible for a number of flares, outbursts of solar cosmic rays, suddenly-commencing magnetic storms and Forbush decreases. Increased absorption was observed from September 15 to September 29, 1963. Two more powerful absorption events (of amplitude ~ 3 db) overlapped the periods from 21st to 24th and from 26th to 29th September 1963. The conditions of the experiments enabled us to directly compare the day/night effects in the ionospheric absorption since when the ionosphere over the station came under the shadow of the Earth, the other station came out of the shadow and both the stations were simultaneously illuminated by the Sun for a few hours.

Masley and Goedeke [11] observed that the riometers at 30 MHz and 50 MHz installed at the above-mentioned stations recorded in all, 12 cases of the beginning of solar cosmic rays. Each of these cases and the consequent phenomena at the Sun are described in [11]. It follows from the time lag between beginning of the absorption and solar phenomena that the protons recorded had an energy of $\mathcal{E}_k$ = 10-30 Mev (in the case of linear propagation). In those cases where the flare occurred at the western part of the solar disk, the time lag was less than 90 minutes whereas for 50% of the cases, the time lag was more than 90 minutes during maximum solar activity. The effectiveness of flares in the western part of the solar disk was, to some extent, more than the effectiveness of flares in the eastern part. The maximum intensity of protons with $\mathcal{E}_k > 0.5$ Mev was 10-7000 $cm^{-2} \cdot sec^{-1} \cdot sterad^{-1}$.

Gillmor [12] has studied the data of riometric observations at magnetoconjugate observatories Mirnyy (Antarctica) and Longyearbyen (Spitsbergen, Arctic). During 1961, five absorption periods were recorded at Mirnyy. About half the cases with amplitude of 0.3 db and three fourth with amplitude of one db, recorded at Mirnyy, were accompanied by considerable absorption effects at Spitsbergen. Considering that frequency of events at Mirnyy was $\sim$ 0.08 hour $^{-1}$, it is highly-improbable that the above-mentioned relation is casual. A thorough investigation showed that in spite of the general correlation between absorption cases, a proper correlation between details of the events — shape and amplitude — is not always observed. The absorption curves were similar when both the stations were simultaneously illuminated by the Sun (July 12-16, 1961) and a large difference was observed at other times. Similar results were obtained during the other absorption events, and this convincingly proves that the fluxes of particles at conjugate points were equal.

An increase in the sensitivity of the measuring equipment facilitates better detection of even weak fluxes of solar particles in the upper layers of the Earth's atmosphere. Gregory [13] described a new method of detecting solar protons in the lower ionosphere by using a highly-sensitive probe for vertical probing of the ionosphere. This probe operates at a frequency of 2.3 megacycles/sec. It helps in recording the flares of solar protons having an amplitude much less than that required by less sensitive riometers. Moreover, the new method helps in obtaining information about the height at which the electron density changes. Measurements taken by this method in 1960 at the geomagnetic latitude of 79°S detected 37 cases of solar proton events, The total duration of all of these events during one year was not less than 167 days.

The analysis of ionospheric effects due to solar protons allows us to understand the peculiarities of chromospheric flares. In particular, it is important to decide whether there exists a sharp division of flares into proton flares and usual flares or whether there is a gradual transition from powerful proton flares accompanied by the generation of a large number of relativistic particles, to medium and weak flares giving rise to hardly noticeable increase in the minimum reflection frequency (f_{min}) at high geomagnetic latitudes and finally to flares for which no effects, are observed in the polar ionosphere. With this objective, A.S. Dvoryashin [14] thoroughly analyzed the ionospheric data of many stations of northern and southern polar caps during the period between the International Geophysical Year (IGY) and the International Geophysical Cooperation (IGC). A number of small increases in f_{min}, connected with weak proton flares, were observed. The flares were identified by considering the nature of the outburst of radio emission. It was considered that simultaneous appearance of an outburst of radio emission of type IV is the main criterion for the occurrence of a proton flare.

As a result of the study of a large number of solar flares and the ionospheric parameter f_{min} in the polar cap, Dvoryashin [14] concluded that there was no clear boundary between proton and optical flares. This conclusion also follows from the analysis of outbursts of radio emission.

Letfus and Nestorov [15] studied the effect of the flux of protons due to May 4, 1960 solar flare on the ionization in the D layer. A good correlation was found to exist between ionosphere absorptions at 27 and 14 kHz and energy spectrum of the protons. It was explained [15] that the ionization in the D layer due to solar particles from May 4, 1960 flare was mainly by the propagation of protons along magnetic lines of force of the spiral-shaped interplanetary field.

I. N. Odintsova [16] made interesting investigations on the ionospheric effects in E and D layers during the chromospheric flare events of class 2 and 3 during the IGY. He studied the dependence of geoactive flares, which gave rise to ionosphere effects in E and D layers, on their positions on the Sun's disk and time of the day. It was found that flares during 13-15 hours local time are most effective in producing ionosphere effects. The dependence of the effectiveness of flares on their position on the Sun's disk was not detected. Time dependence between beginning of the optical flare in H_α and the beginning of effect in E and D layers was also studied. It was observed that the effect in E region was observed simultaneously with the optical flare whereas the effect in the D layer started somewhat later. However, there are number of cases when the effect in E region starts before the start of the H_α flare. The time difference between commencement of the effects in D layer and the E layer is of the order of a few minutes. [16]. In order to explain this time difference, it has been assumed that the soft roentgen (X-ray) radiation of the flares, which is responsible for the effect in E layer, originates much earlier than the hard radiation that affects the D layer. Recently, a number of authors showed that an increase in the electron density in the F_2 layer is also observed during some flares. Following are such flares: November 19, 1949; February 23, 1956; July 10, 1959; November 12, 15 and 20, 1960; July 11, 12, 18 and 21, 1961. All these flares were accompanied by an increase in the intensity of cosmic rays at the sea level or in the stratosphere.

On the other hand, Knecht and Davies [17] have suggested that the effects in F_2 layer, just like those in E and D layers, are caused not by cosmic rays but, obviously, by unusual photon radiation originating due to flares which give rise to cosmic rays. In this connection, I.N. Odintsova [18] analyzed five additional cases of the effects in F_2 layer during the chromosopheric flares of class 3 and 3+ that were observed on September 21, 1957; March 3, 23, and 5, 1958 and on August 22, 1958. The comparison with the data given by A.S.

Dvoryashin et al. [19] showed that only three of these cases, namely those observed on September 21, 1957, March 23, 1958 and on August 22, 1958, were accompanied by the propagation of fast proton with ε_k = 10-100 Mev to the polar cap and thus caused polar cap absorption of radio waves.

Analysis of data on the minimum reflection frequency obtained at three high-latitude stations (Hayes Peninsula, Resolute and Cape Hallet) by L.S. Levitskii [20] during 1963 revealed 9 distinc ses of increase in f $_{min}$. Morevoer, it was possible to related 8 of these cases unambiguously to chromorpheric flares observed on April 15 at 1034 UT (class 2, flare), May 1, at 0525 UT (class 2 flare), August 6 at 0855 UT (class 2 flare), August 9 at 2234 UT (class 1 flare) September 15 at 0015 UT (class 2 flare), September 16 at 1300 UT (class 2 flare), September 20 at 2314 UT (class 2 flare) and on September 26 at 0638 UT (class 3 flare). All these flares were accompanied by outbursts of radio emission in a wide range of frequencies half of which belong to type IV outbursts. Invasion of solar protons in the polar ionosphere on April 15 and on September 1963 was also confirmed from the riometer data magnetoconjugate points McMurdo (Antarctica) and Shepherad (Canada) (see [81], [10] and [21]).

Wilson and Nehra [22] have observed that only those solar flares which are accompanied by absorption of short radio waves in D layer of the ionosphere at low latitudes give rise to the effect in cosmic rays. Now, it has been reliably established that these absorptions in the D layer (just like other ionospheric effects associated with additional ionization of D-layer at low latitudes) are caused by the outburst of X-rays of wave length $\lambda \lesssim 8$ Å. B.M. Vladimirskii and A.K. Pankratov [23] by using different techniques of analysis and processing of data obtained during IGY and IGC for flares of different classes, and other associated ionospheric effects have also confirmed the results obtained by Wilson and Nehra [22]. It was shown that all the chromosopheric flares accompanied by significant increase in ionospheric absorption do not give rise to an increase in the intensity of cosmic rays. Existence of a relation between X-ray radiation of flares ($\lambda \lesssim 8$ Å, $h\nu \gtrsim 1.5$ kev) and relativistic part of the spectrum of solar particles ($\varepsilon \gtrsim 1$ Gev) can, in principle, be understood by assuming, firstly, that the X-ray radiation responsible for ionospheric effects is mainly due to the retardation of super thermal electrons (synchrotron radiation of these electrons is possibly observed as radio outbursts of type IV) and secondly, that the electrons responsible for X-ray radiation are accelerated during the growth phase of the flare to same velocities as those of nuclei or their secondaries (in both the cases, the ratio of average energies of the nuclei and electrons will obviously be equal to the ratio of their masses). Thus, from the above point of view, the presence of a outburst of X-ray radiation testifies to the existence of electron component of solar cosmic rays.

Important results about the relation between X-ray radiation and the effects of chromospheric flares in cosmic rays were obtained by B. M. Vladimirskii and A.K. Pankratov [24] by comparing the ionospheric effects to small ($< 1\%$) increases in the intensity of nucleon component at sea level. It was shown that; (1) on an average, more significant increases in cosmic rays at sea level correspond to stronger effects in the D layer of the ionosphere; (2) the appearance of increased absorption in D layer, which is due to the beam of X-ray radiation of $\lambda \lesssim 8$ Å, is the necessary but not sufficient condition for the origin of a small effect in cosmic rays at sea level.

A. S. Dvoryashin [25] considered the peculiarities of X-ray radiation due to proton flares. His study is based on the investigation of time variations of ionospheric effects corresponding to the proton flares. The increase in the hardness of the spectrum of the X-ray radiation has been established for a number of flares This radiation most probably originates during the retardation of high-energy protons in the dense layers of the chromosphere (unstable radiation). It is interesting to mention that emission of X-ray radiation from the active region of the Sun has been observed [25] for a number of powerful flares only after the brightening of the flare in the H_α has been practically reduced. Obviously, this radiation is stable and has its source on plasma, existing in the coronal condensations. Moreover, the extension of the brightening in H_α to the spot or penumbra of the spot at the time of maximum of the flare points out the fact that the mechanism which excites the brightening in H_α, is situated in the magnetic field. Since the outburst of centimeter radio emission which is due to synchrotron radiation of electrons, attains maximum at the same time, the transient process leading to the acceleration of particles and heating of the plasma, is also believed to be localized in the magnetic fields.

Recently, Wilson and Nehra [26] detected a small increase in neutron component at the Sulfur station (geomagnetic latitude 58° N) and not so reliably, at the Resolute station (83° N). These increases were caused by powerful solar flares accompanied by absorption of short radio waves known as short wave fade-outs (swf). Some of the fade-outs are also accompanied by another effect known as the so-called geomagnetic crochet which is due to the increase of electron density in the ionosphere. This effect is caused due to the sudden change in geomagnetic field corresponding to the increase of currents in the lower ionosphere. Since flares of cosmic rays and geomagnetic crochets are correlated to fade-outs, it is important to explain if there exists any specific relation between them. Warwick's calculations [27] show that at Sulfur station, cosmic rays flare which also produce the crochets, should have an amplitude of 0.05 % whereas observations show it to be 0.2-0.3%. On the other hand, it is known that small outbursts of cosmic rays are usually revealed during the statistical analysis of the ionospheric effects of a large number of solar flares. If the increase is caused only by the effect of crochet, the calculated amplitude must be more than the observed one. Otherwise, it is difficult to explain the fact that some flares are accompanied by fade-outs and not by geomagnetic crochets. Thus, it is less probable that the increase observed at Sulfur station can be fully explained by the effect of geomagnetic crochet. Even then, the effect of the crochet is very significant and it cannot be neglected while analyzing small increases in the intensity of cosmic rays.

Similar conclusions were drawn in the same work [26] from the results of statistical analysis of solar flares of class $\geqslant 2$ observed during 1959-60. During this period, 85 flares accompanied by fade-outs were recorded and 60% of these flares were observed during the time when it was night at Sulfur station. It was shown that one out of every three short wave fade-outs is related to the effect of magnetic crochet which however can only be observed during day time. Thus as mentioned earlier in [26], the effect of crochet on the counting rate of neutron monitor at Sulfur station must have an amplitude of approximately 2% so that it may be possible to explain the 0.25% increase in the intensity of nucleon component as mentioned by the authors in [22]. However, due to certain reasons, it is assumed in [26] that the effect of crochet has a value less than the amplitude of the increase in nucleon component, mentioned in [22], by two orders. Moreover, time scales of the effect of the crochet are considerably less than the duration of the increase to the maximum value of the intensity of cosmic rays. Thus, the increase in the intensity of cosmic rays can obviously be explained by the propagation of the solar particles to the Earth without giving rise to the magnetic crochet effect. However, the effect of geomagnetic crochet on neutron component is not eliminated during years of minimum solar activity and may be detected from the data recorded by supermonitors.

The relation between solar flares and geomagnetic crochets was also studied by Pinter [28]. In all, 29 cases of the occurrence of the crochet during 1954-65 were studied. Two maxima in the frequency of the occurrence of this effect (1957 and 1960) were also observed. It was shown that the geomagnetic crochets that are related to powerful proton flares are observed at stations separated by $\lesssim$ 5-6 hours with respect to the subsolar point. As a result of the analysis [28], it was confirmed that solar X-ray radiation which has an effect on the mechanism of producing crochet reaches the D layer.

A large amount of data on absorption in the polar cap during the year 1952-63 were analysed by Dodson and Hedeman [29] in order to understand the periodicity of these events and relate them to the average period of rotation of the Sun ($\sim$ 27.3 days) and the Moon ($\sim$ 29.5 days) . In the latter case, a clear deviation from the arbitrary distribution was observed. It is still not clear whether the observed 29.5 day effect is related to the Sun and the Moon or is only a statistical randomness.

Van Allen et al [30] studied the relation between the absolute flux of solar protons and the amplitude of polar absorptions. Eight different cases of increase in the flux of solar particles during 1960 were studied. The investigation was made with the data obtained by the satellite "Explorer-7" which measured the tofal intensity of particles I ($> \varepsilon_*$), where ε_* = 30 Mev for protons and 120 Mev for α-particles. Data on simultaneous riometric measurements of the absorption amplitude A of cosmic radio noise at a frequency of 27, 6 MHz at Thule and College stations were used for comparison purposes. Values of $A/I_0^{1/2}$ and $I_0/A^0 = H_*$ were calculated as functions of kinetic energy ε_k for monoenergy protons and α-particles separately. It was shown that various narrow ranges of the values of experimental parameter H_* can correspond to three different possibilities: atmospheric absorption is mainly used by particles having energies 1) $\varepsilon_k < \varepsilon_*$ 2) $\varepsilon_k \approx \varepsilon_*$ or 3) $\varepsilon_k > \varepsilon_*$. For the different cases, the observed values of H_* change from 40 to $< 10^{-2}$ db^{-2} cm^{-2} sec^{-1}. During a given event, H_* either remains constant or decreases (sometimes considerably). It follows from [30] that polar absorptions are mainly caused by the complex beam of protons of energy $\varepsilon_k < 30$ Mev and α-particles with $\varepsilon_k < 120$ Mev or independently by beams of these particles having the same energy. For a given event, the shape of the spectrum for the given values of the energy changes considerably for different cases and has a tendency to remain the same or become steeper with the passage of time*).

In the translated collection edited by Ya. I. Fel'dshtein [31], there are 11 articles describing the set of geophysical phenomena related to ionospheric polar cap absorption (PCA).

A number of important results on the nature of propagation and accumulation of high-energy solar particles in the

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*) *By analyzing minimum reflection frequencies (f_{min}), data of riometers and magnetometers during some proton flares for a number of stations situated at geomagnetic latitudes of 50-70°, Lichtenstein [91] showed that the moments of commencement of the phenomena change with time in an arbitrary manner. It is so owing to different times of propagation of groups of particles having different energies.*

interplanetary space and the effect of the Earth's geomagnetic field on the motion of these particles have been obtained by Leinbach [32] in his voluminous work, which was based on the analysis of data obtained by riometer on time variations of polar cap absorptions. Holt [33] analyzed the data of riometric observations obtained at some stations at a frequency of 27.6 MHz during the years 1958-62 Hargreaves et al.[34] using the riometer data on 26.5 MHz at the South Pole during the period December 1962- April 1964, studied the events of auroral absorptions which are most-clearly observed during 00.00-0300 and 1400-1500 UT which correspond to ~ 10 and 21 hours local geomagnetic time.

Peculiarities of auroral absorptions at the South Pole, observed in [34] during day and night hours of local geomagnetic time, are explained by the change in the characteristics of high-energy particles invading the ionosphere.

From a study of riometric data obtained during 1961-63 at some stations at Alaska, Parthasarthy and Berkey [35] attempted to explain the morphological peculiarities of suddenly-commencing absorption (absorption of the type F). A study of the seasonal and daily variations in the number of absorptions of this type has been made. The maximum number of absorptions is observed during the autumnal equinox and the minimum number before the vernal equinox; a daily maximum is observed at midnight. The amplitude distribution of the number of type F absorptions has also been obtained. The decrease of cosmic noise by 1.5-2 db is observed most often. An analysis of type F absorptions at different frequencies in the range 5-50 MHz has also been made with a view to study the electron concentration at different altitudes in the lower ionosphere. It has been concluded that the energy of the corrrsponding primary particles, during the absorption time is by a few orders more than that of particles giving rise to aurora.

Hakura [36] calculated the corrected geomagnetic coordinates of 100 high-latitude ionsopheric stations by considering higher harmonics of dipolar series. Two typical cases of polar cap absorption observed during February 10-12, 1958 and May 6-8, 1960 were analyzed with the help of these coordinates.

Blackout isolines, having oval shape in the system of coordinates related to central dipole, became absolutely circular in the corrected system and that made it possible to unambiguously define cut-off latitude of the solar particles giving rise to the absorption. This latitude is well in conformity with the latitude distribution of solar particles obtained from satellite data.

On the basis of numerous data obtained during May 1957 and May 1960, an attempt has been made in G. M. Khocholava's works [37, 38] to ascertain the factors that define the distribution of the two types of abnormal polar cap absorption -- simultaneous and gradual -- as suggested by many authors. In the case of the first type of absorption, there will be small delay between the beginning of a chromospheric flare and simultaneous extension of absorption to the whole of the polar cap whereas in the case of second type the absorption starts at one or a few stations and gradually covers whole of the polar cap but the absorption at the initial stages (sometimes even during the first 10-15 hours) is complete (only the level of minimum reflection frequency is raised). As a result of the detailed analysis, it is shown in [37, 38] that, for differentiating the two types of absorptions, $\Delta T = 10$ hours should be considered as the limiting value of the time lag of arriving particles with respect to a solar flare. Here, it is not the heliolongitude of the flares giving rise to abnormal absorption but the dimensions of the magnetic trap of the corpuscular beam is the deciding factor. The dependence of the time lag ΔT (hours) on the intensity of the magnetic field of the trap H_t (gamma) can be described as $\Delta T = 1.28 \exp(0.4 H_t)$. The correlation coefficient for the values of ΔT and magnetic field of the trap is equal to 0.92.

The relation of polar absorptions with the nature of the interplanetary magnetic field and Forbush decrease in the intensity of cosmic rays is considered by a number of authors.

Haurwitz et al. [39] studied the dependence of altitude distribution of polar cap absorption and Forbush effects on the heliographic longitude of the corresponding flares. Large increase in absorption during the period of sudden commencement of the magnetic storm and strong Forbush effects are caused almost exclusively by eastern and central flares. In this connection, it has been assumed that plasma, moving from flares has a deciding role in giving rise to the asymmetries in the interplanetary magnetic field with respect to the Sun-Earth line. It is shown that this asymmetry arises as a result of the interaction between widening solar plasma and quiet spiral-shaped magnetic field. Obviously, this asymmetry is the main cause of the difference between the phenomena in the polar cap and Forbush effects related to eastern and western flares.

Swestka [40], verified and critically selected cases of radio outbursts of type IV and polar absorptions and compared them with Forbush effects observed during 1956-63. A clear predominance of flares of the western hemisphere of the Sun for the cases producing intense absorptions and of eastern hemisphere for strong Forbush effects is observed. This result indicates the asymmetrical distribution of magnetic field in the cloud of ejected particles and the presence of a clear magnetic boundary on the west.

Gosling [41] observed that absorptions after the sudden commencement of the storm are accompanied by Forbush effects considerably stronger than the absorptions before the storms. It follows from this that corpuscular beams in the first case carried strong magnetic fields with traps of solar cosmic rays. Moreover, the delay in the commencement of the storm with respect to the flare in the first case is significantly less than that in the second case.

The relation between the peculiarities of propagation of solar cosmic rays and characteristics of geomagnetic storms is analyzed in a number of works. In particular, Yoshida and Akasofu [42] considered the dependence of the characteristics of storms of cosmic rays (Forbush decrease) and geomagnetic storms (K_p and D_s) on the distance from the central meridian of the corresponding solar flares. The storms are grouped together according to the characteristics of preceding solar particle flares. It may be mentioned that the "center-edge" effect can be observed only by grouping the storm in this way. By considering this effect, it was shown that solar flares , which were related to an unusual increase in the intensity of cosmic rays, contain the most energetic solar particles, impart maximum amount of energy to magnetic storms and give rise to the strongest Forbush effects.

Bhargava and Subrahmanyan [43] studied the relation between amplitudes of sudden geomagnetic storm commencements and the other associated characteristics of solar flares such as radio and optical radiation, energy of generated particles. It was shown that all the cases of sudden commencement with amplitude more than some threshold minimum at a given mid-latitude station, were related to the events of the appearance of solar cosmic rays. The dependence of the time of propagation of plasma, giving rise to the magnetic storm, on the position of flare on the Sun's disk is also studied. The question of the increase in the amplitude of sudden commencement in equatorial regions is considered as well. The amplitude characteristics of the sudden commencement events have been used for identifying about 50 cases of the origin of solar cosmic rays during the cycles No. 12-18 of solar activity.

Keppler [44] studied the effects which sometimes precede the sudden commencement (SC) of the geomagnetic disturbance. In particular, the data obtained at Kiruna station before the July 13, 1961 SC, arising as a result of the July 12 solar flare, are analyzed in detail. A gradual increase in X-ray radiation ($\varepsilon_\gamma \leqslant 100$ kev) which started about three hours before SC was observed. The intensity of X-ray radiation before the SC increased up to 80 photon$\cdot$cm$^{-2}\cdot$sec$^{-1}\cdot$ sterad^{-1} and at the time of SC, it abruptly increased to 10^3 photon$\cdot$cm$^{-2}\cdot$sec$^{-1}\cdot$ sterad^{-1}. The increase in the flux of X-ray radiation before the SC is explained as due to the emission of radiation caused by retardation of electrons having an energy of a few kev; flux of such electrons must be of the order of 10^9-10^{10} electron$\cdot$cm^{-2} sec^{-1} An analysis of the observations also showed a gradual increase in the flux of protons with an energy of a few Mev before the SC. After the SC, the flux of these protons suddenly decreased, increased very quickly to a still higher value and then gradually decreased to the normal level. It was assumed that the high-energy electrons, which gave rise to the increase in the flux of X-ray radiation and protons, appeared in the interplanetary space as a result of the acceleration between standing shock wave front before magnetosphere and the moving shock wave front which appeared at the front edge of the plasma cloud which was ejected out of the region of the flare. This assumption, was first put forward by Axford and Reid [1.62] and later confirmed by observation. For explaining the proton effects after the SC, it was assumed that protons with energy of a few Mev exist in the plasma cloud itself. Diffusion of these protons from the cloud contributes most to the proton flux after the sudden commencement of a geomagnetic disturbance.

Obviously, the magnitude of the absorption effects should considerably depend on the spectrum and composition of the solar cosmic rays. Let us review some of the works where this dependence is studied.

Velinov [45] obtained a formula for electron density due to cosmic rays at a height in the lower ionosphere but his formula is applicable only to particles with $\mathcal{E}_k > 3\text{-}4$ Gev/nucleon. However, particles even with less energy penetrate to geomagnetic latitudes $> 55^\circ$. Moreover, the cut-off rigidity may be reduced during disturbances (for example, in the case of chromospheric flares accompanied by ejection of particles and by geomagnetic storms) and in such cases, particles, with energy considerably less than 3 Gev will propagate to medium latitudes. These particles intensify ionization even at medium latitudes. In this connection, Velinov [45] suggested another more general formula for arbitrary index of the spectrum of cosmic rays which is applicable within a wide range of energies (also of solar protons). The lower limit of the applicability of the formula is limited energies of the order of a few kev when other ionization mechanisms start playing the leading role.

According to Freier and Webber [III. 6], the rigidity spectrum of the solar particles in the energy range from a few kev to a few Mev can be expressed as $D(R) \sim \exp(-R/R_0)$ where rigidity characteristic R_0 changes from 0.03 to 0.2 Gv. In particular, the mathematically simple form of the spectrum, applicable within a wide range of energies, facilitates quantitative analysis of ionospheric effects of solar cosmic rays. For example, in another work of Freier and Webber [46], the observed electron density profiles in the ionosphere were compared with the profiles calculated from the data of balloon measurements on cosmic rays. Ionospheric measurements were conducted at geomagnetic latitudes of 70° with the help of riometer which records the absorption of the radio waves of frequency 30 MHz. Electron densities predicted on the basis of ionospheric parameters and on the basis of exponential rigidity spectra [III. 6] are well in agreement with the measured profiles. In the case of certain flares, application of Kane's [47] collision frequencies ν in the ionosphere along with the expected electron densities gives absorption values less than the observed ones. Obviously, this difference is explained by the role played by solar α-particles. The events of May 10-12, 1959, July 10-17, 1959, September 3, 1960, November 12-17, 1960 and of July 18-20, 1961 are analyzed in detail.

For estimating the relative role of the solar α-particles in producing polar absorption, Weir and Brown [48] also made use of exponential rigidity spectrum [III. 6] for a number of strong absorption events. In order to get absolute values of ionospheric parameters, computations were made on the basis of experimental data on flux, spectrum and relative composition of solar cosmic rays. The rate of formation of electrons, their density and specific absorption versus height were calculated for a beam of solar particles containing equal amounts of protons and α-particles ($p:\alpha = 1$) for a station with cut-off rigidity $R_{min} = 470$ Mev. The results obtained show that α-particles at the ratio $p:\alpha = 1$ give rise to about 75% of the ionospheric absorption. Commencing from an altitude $h \geq 50$ km, the rate of formation of electrons as a function of altitude is less by about one order in the case of purely proton beam than that for a beam of only α-particles.

As mentioned by Brown [49], the assumption of an exponential form of rigidity spectrum for solar particles, to a great extent, eliminates the difficulties involved in the explanation of latitudinal effect of polar absorptions. However, the question of the magnitude of absorption remains unsolved especially for magnetically quiet days. This is because the model of ring currents, suggested by Kellog and Winckler [I. 66] for a magnetic storm, is not suitable for explaining small local cut-off rigidities. This drawback can apparently be compensated by considering the role of the solar α -particles in the ionization process of the upper atmosphere. Computation of Weir and Brown [48] showed that a considerable fraction of absorption can actually be explained by solar α-particles. However, this result is obtained by extrapolating the rigidity spectrum of protons and α -particles to the regions where the rigidities are lower than those accessible to measurements.

In the absence of additonal data on solar cosmic rays in the region of low rigidities, it is interesting to consider other effects in addition to ionospheric absorption for explaining the validity of this extrapolation. It is all the more desirable due to the fact that absorption calculations must take into account certain processes (ionization, recombination and absorption) each of which has its own uncertainities. Some of the new possibilities in this direction help in observing photon emission in the atmosphere during solar flares.

5.2 Polar-glow aurora. With the aid of spectrographic observations at high geomagnetic latitudes during powerful flares of solar cosmic says, Sandford [50, 51] showed that the bombardment of polar atmosphere is accompanied by weak optical illumination (the so-called polar-glow aurora) whose intensity is sometimes comparable to the intensity of Milky Way. The maximum intensity of this radiation is observed at a height of about 65 km. The polar-glow aurora is usually attributed to one of the negative transitions in the ionized nitrogen molecule N_2 + (for example, the transition with wave-length of 3914 Å). This effect has extremely slow time variations similar to the variations in the absorption of cosmic radio noise in the polar cap. The intensity of the radiaion is a direct measure of the energy carried by solar particles to the atmosphere.

Brown [52] calculated the expected intensities of 3914 Å line on the basis of the exponential rigidity spectrum [III. 6] and compared the obtained results with Sandford's observations

[50, 51]. The time variations of the radiation are well in agreement with the calculated results whereas the observed intensity of the radiation is about 10 times the calculated value. These differences are apparently related to the uncertainities in the spectrum of solar particles, to the absolute calibration of spectrograph etc. Ionization profile calculations, made by Brown [52] in connection with the study of polar absorptions, show that the ionization (and excitation) processes are mainly limited to dense atmospheric layers. In particular, the radiation due to 3914 Å line arises below 100 km. It is in conformity with Standford's observations [50, 51] in which the increase in the intensity of twilight illumination in 3914 Å line was not observed during the time of absorption events when the atmosphere below 100 km is illuminated by the Sun.

The presence of the forbidden line of atomic oxygen 5577 Å is another important characteristic of polar-glow aurora. This line gives rise to more irregular time variations as compared to 3914 Å line but, in general, they are similar at least before the commencement of the magnetic storm caused by the chromospheric flare which is responsible for the outburst of cosmic rays. After the commencement of the storm, 5577 Å line is more intense than 3914 Å line mainly owing to the propagation of plasma cloud to the Earth. Up to the commencement of the storm the intensity of 5577 Å line is however 1/5 that of 3914 Å line. This conclusion was drawn by Standford [50, 51] on the basis of observations on absorption events during July 1959.

The number of particles coming into the atmosphere at a given station depends on the local value of cut-off rigidity. However, since protons and α- particles with the same rigidity have different absorption mean free paths in air, the degree of ionization (and excitation) at a given altitude may considerably change depending upon the relative content of protons and α - particles in solar cosmic rays. Moreover, for a given flux of particles the degree of ionization (and excitation) at a particular altitude will depend on the form of spectrum, namely, on the rigidity R_0 in the exponential spectrum [III. 6]

As already mentioned, the emission of 3914 Å line is caused by permissible transition in ionized nitrogen molecule from a state excited simultaneously with N_2 ionization, so that the profile of this line followed closely the ionization profile obtained by bombarding the Earth's atmosphere with solar particles. On the other hand, the emission of 5577 Å line is caused by forbidden transition 01. Since the metastable state which gives rise to this radiation, is strongly disturbed due to collisions in the dense layers of the atmosphere, the profile of 5577 Å line is considerably shorter than the profile of 3914 Å line. Thus, the ratio of intensities I (5577 Å)/ I (3914 Å) = k can serve as a measure of the amount of energy dissipated in an extremely limited layer at an altitude of about 90 km. As shown above, this ratio depends upon the composition and form of the spectrum of solar particles and therefore, can change during the same event or from event to event [52]. According to Brown's estimates [52], the presence of α- particles in the spectrum of solar cosmic rays increases the ratio k and at the same composition but steeper spectrum, the value of k also increases. A change in the composition and spectrum of solar particles during a given event independently leads to an approximately the same change in the value of k. Energetic beams, necessary for exciting the polar-glow aurora to a noticeable intensity, were observed only during powerful polar absorptions, for example, during May-July 1959 and November 1960. In other less intense cases, it is hardly possible to expect aurora whose intensity may be more than that of night sky. On the basis of the calculations done by Brown [52], it is concluded that the intensity of 3914 Å line depends on the flux of energy carried by solar cosmic rays whereas 5577 Å radiation is much more sensitive to the changes in the composition and rigidity R_0 in the spectrum of solar particles since this radiation arises as a result of some processes taking place in the limited atmospheric layer.

5.3 Generation of γ-radiation in the upper layers of the atmosphere. The γ-radiation apparently originates as a result of nuclear reactions between solar particles and the Earth's atmosphere. Such a radiation was recorded for the first time on balloons by Hofmann and Winckler [53] and Keppler et al. [54] during the middle of July, 1961.

During the experiments undertaken by Hofmann and Winckler [53] during July 12-14, 1961 over Churchill (68.7°N), the recorded photons had $\mathcal{E}$ = 20-60 kev which is significantly higher than the energy of X-rays accompanying the polar auroras. Low-energy protons responsible for γ-radiation were apparently generated by class 3^+ flare at 1000 UT on July 12, 1961. This was confirmed by the satellite "Injun-1" which recorded solar protons with $\mathcal{E}_k \gtrsim 1.5$ Mev at a distance of about 1000 km from the Earth's surface. Their intensity increased right up to the arrival of the corpuscular beam to the Earth which caused a magnetic storm with a sudden commencement at 1112 UT on July 13, 1961. From this it was assumed in [53] that there could have been weak capture of low-energy protons near the forefront of the beam. According to the data obtained by "Injun-1", satellite, the decrease in their intensity in the Earth's environment continued for a few days.

According to observations made by Hofmann and Winckler [53], the penetration of γ-rays with $\mathcal{E} > 60$ kev is similar to the penetration of photons with $\mathcal{E}$ =20-60 kev. From this, it can be concluded that the recorded photons are formed in nuclear reactions of low-energy protons at the atmospheric boundary and actually have an energy of the order of a few Mev and a very steep spectrum; but they lose only an insignificant fraction of their energy in the crystal of scintillation counter.

Simultaneously with the commencement of the magnetic storm, in addition to γ-rays with $\mathcal{E}$ =20-60 kev, a significant flash of low-energy photons of duration of nearly 6 minutes was recorded over Churchill. These photons most probably represent retardational X-ray radiation of electrons which is related to some unknown mechanism of abnormal acceleration of electrons in the Earth's surroundings. The electron flux, necessary for the formation of these photons, will be of the order of 10^9 $\text{cm}^{-2}.\text{sec}^{-1}$. In order to explain the recorded flash of photons by nuclear reactions in the atmosphere, it is necessary to postulate some very complicated acceleration mechanism, within extremely rigid limitations, on the behavior of protons trapped near the front of magnetic cloud which had given rise to the geomagnetic storm.

Balloon measurements conducted by Keppler et al. [54] during the same period at Kiruna (Sweden, 65.3°N) confirm the results obtained at Churchill. It is interesting to note that similar measurements at Minneapolis (55.1 °N) gave negative results. This can be expected by explaining the γ-radiation only with the help of low-energy protons, since the geomagnetic field at Minneapolis allows the particles with $\mathcal{E}_k \gtrsim 400$ Mev to pass under normal geomagnetic conditions. On the other hand, the geomagnetic threshold at Churchill is apparently of the order of only a few Mev.

An account of the basic methods and results of the investigation on ionospheric effects of solar cosmic rays is given in Bailey's detailed review article [17] in which works published up to January 1964 are included.

5.4 Solar cosmic rays and isotopic composition of air. Some amount of radioactive isotopes (C^{14}, H^3, Be^7, P^{32}, S^{35}, Cl^{39}, K^{40}, etc.) are formed in the Earth's atmosphere due to nuclear reactions of cosmic rays. Recently, Craig [55], Begemann and Libby [56] showed that the measured production rate of tritium H^3 was considerably higher than that expected on the basis of the generally adopted intensity of cosmic rays.

In order to explain the abnormally high content of tritium in the Earth's atmosphere, Begemann [57] suggested that, in addition to nuclear reactions of normal beam of cosmic rays, following two sources also must be considered; (1) propogation of high-energy tritons generated at the Sun, and (2) additional formation of tritium by low-energy component of cosmic rays during minimum solar activity. Simpson [58] drew the attention to one more powerful source of tritium H^3 and radioactive carbon C^{14} namely, the arrival of solar protons which are caused by chromospheric flares, to the Earth in the region of high latitudes. Solar flares of class 3 and 3^+ are a source of powerful beam of solar protons with $\mathcal{E}_k = 80\text{-}400$ Mev, average integral spectrum $\sim \mathcal{E}_k^{-4}$ and with total flux of $\sim 10^4$ proton cm^{-2} sec^{-1} at the boundary of the Earth's atmosphere. About 30 such events were observed during the last cycle of solar activity. Considering that the average energy of primary particles of a normal beam of cosmic rays is about 4 Gev and taking 100 Mev for solar protons, we find that the production of H^3 and C^{14} per particle of solar cosmic rays is less than that per particle of galactic cosmic rays by 20 times. On the other hand, considering that the solar protons are emitted for about 0.01 times of the total time, it can be shown that the average rate of production of H^3 and C^{14} in the Earth's atmosphere by solar protons can be about 3.5 times the rate of production of these isotopes by a normal beam of cosmic rays. According to the data analyzed in [1, 2], the spectrum of solar protons is stretched in the region of sufficiently low energies, and because of this the total flux of protons at the atmospheric boundary in the region of polar caps can be even more than that adopted by Simpson [58].

Isotope C^{14} originates in the atmosphere during the interaction of neutrons of galactic cosmic rays with the atmospheric nitrogen. According to Lingenfelter and Flamm [59], the average production rate of C^{14} is 2.5 atom.cm^{-2}. sec^{-1} whereas the dissociation rate is equal to 1.8-2.0 atom. cm^{-2}. sec^{-1}. It is assumed that the secondary neutrons, produced by solar protons during strong chromospheric flares, can be the additional source of formation of C^{14}. The role of solar protons was computed from an analysis of the data on their spectrum and intensity during 1956-61; moreover, in this case, the exponential spectrum of rigidity was used for the analysis. The value $dI/dR = 2\exp(-R/125)$ proton.cm^{-2}.sec^{-1}. Mv^{-1} or I ($>$100 Mv) = 4 proton. cm^{-2}. sec^{-1} was obtained for the average flux during a solar cycle. These data were used for calculating the equilibrium distribution of neutrons in the atmosphere with respect to height and latitude. Thus, a value of 0.44 atom. cm^{-2}. sec^{-1} was obtained for the production rate of C^{14} in the polar regions. This value with an accuracy of $\pm$ 10%, remains constant for cut-off rigidities $R \lesssim$ 400 Mv and later on decreases to $\sim$ 0.04 atom. cm^{-2}.sec^{-1} at $R \approx$ 1.1 Gv. The average production rate of C^{14} is approximately equal to 0.05 atom.cm^{-2}.sec^{-1} for normal dipolar field and it increases to 0.12 atom.cm^{-2}.sec^{-1} if one considers the decrease in cut-off rigidity during certain flares of solar cosmic rays. It may be mentioned that the obtained values for the rate of production of C^{14} by solar protons are within the limits of the error in the determination of the rate of production of C^{14} by galactic cosmic rays. It also follows from the calculations [59] that a deviation of 1-14% in the content of C^{14}, observed from year to year, cannot be explained by the effect of solar cosmic rays.

Thus, from all the available information considered in this Section, it is not possible to estimate the actual role of solar cosmic rays in the isotopic composition of the Earth's atmosphere without undertaking additional investigations. Even then, some effect of solar particles on the change in the isotopic composition, undoubtedly, exists.

6. THE NATURE OF THE EFFECT OF SMALL FLARES OF COSMIC RAYS

The relation between the observed ionospheric effects and small ($<1\%$ in the neutron component) increases in the intensity of cosmic rays at the sea level has already been mentioned in Section 5. It is known that even very powerful solar flares do not give rise to noticeable increase in the intensity of cosmic rays. Therefore, it is very important to explain as to why the remaining solar flares generate high-energy particles. Some information on this problem can be obtained from a statistical analysis of small increases in the intensity of cosmic rays in relation to other helio- and geophysical phenomena.

The effect of weak chromospheric flares on neutron component was studied by many authors (see the review in [1, 2]). However, their results do not agree among themselves completely. A large number of new papers have appeared recently. In particular, L.I. Dorman et al. [60] studied the effects of increase in neutron component for 165 chromospheric flares of class ≥ 2 during the years July 1957-December 1958 for magnetically quiet days by the superposed epoch method. The analysis of the data of 23 stations has revealed an increase in the intensity of flares within the limits 0.0-0.2%. The effects of flares, accompanied by absorption of type III which indicated the arrival of low-energy particles at high latitudes, were also studied. With this end in view 20 most powerful chromospheric flares--14 of class 3 and 3^+

and the rest of class 2 and 2^+ -- were selected. The increase in the neutron component was found to be 2.5% for medium - and high-latitude stations, and 1% for equatorial stations. It follows from this that the low-energy as well as the high-energy particles are generated during flares accompanied by absorption of type III. This fact allows us to draw a number of important conclusions. The appearance of type III absorption indicates that favorable conditions exist for the generation of low-energy particles and also for their propagation through the interplanetary space to the Earth. The small effect due to high-energy particles points out to the fact that an acceleration mechanism operates in the region of flares which gives rise to a very steep spectrum.

Investigation on the effects of weak flares in the rigid components of the spectrum makes it possible to extend the spectrum of solar cosmic rays to the high-energy regions. However, the problem of the nature of this effect remains unsolved up to this time. There are two different views. According to N.S. Kaminer [61] and L.I. Dorman et al. [62], the increase in the intensity is completely caused by meteorological effects whereas Maeda and Patel [63] and E.V. Kolomeets [64] consider that the generation of relativistic particles during chromospheric flares is the cause of this effect. In particular, N.S. Kaminer [61] and L.I. Dorman et al. [62] substantiate their assumption with the argument that the relation between the increase in the neutron and rigid components is not retained during large and small flares of cosmic rays. However, E.V. Kolomeets [64], showed that this relation is different for different flares. It can change by more than an order and probably, depends on the conditions of the origin of spectrum in the region of chromospheric flare as well as on the electromagnetic state of the interplanetary space. On the basis of analysis of the effect of about 170 chromosopheric flares of class $\geqslant$ 2 obtained from the world network of stations, L.I. Dorman et al. [65, 66] found the increase in the rigid component to be 0.1% i.e., considerably less than that obtained by Dolbear et al. [67] and L.I. Dorman and E.V. Kolomeets [68] ($\sim$0.3%).

The analysis of the results obtained in [64, 66, 68] makes it possible to conclude that the effect in the rigid component is apparently caused by two factors. For example, about 75% of the outburst amplitudes at the equator are mainly explained by meteorological effects which are related to the action of ultraviolet radiation of the solar flares on ozone layer and the subsequent change in the temperature of the upper atmosphere. It should be pointed out that both the factors play significantly different roles at different latitudes: the first factor predominates (low cut-off rigidity) at high latitudes and the second factor is insignificant (large zenith angle of the cone of ultraviolet radiation) whereas at low latitudes, the second factor predominates and the first one is insignificant (due to high cut-off rigidity and small zenith angle of the cone of ultraviolet radiation).

Based on the data of continuous recording of the rigid component of cosmic rays obtained with the help of Yakutskii complex of ground and underground installations during 1957-59, A.I. Kuz'min [69] conducted an interesting investigation on the problem as to whether chromosopheric flares lead to a decrease in the temperature of the stratosphere. As a matter of fact, in accordance with Dorman - Fein theory of temperature effect [1.1], it should be expected that the intensity of cosmic rays at a height corresponding to 60 mv.be should decrease with the decrease in the temperature of the stratosphere while the intensity at the Earth's surface should increase. After making necessary corrections for the barometric effect and the average solar daily variation, it was shown by the superposed epoch method, in [69] that for 87 flares within the limits of experimental error, changes in the intensity of cosmic rays are not observed at any of the undergound levels. It follows from this that, if the effective temperature of the stratosphere changes during the time of chromospheric flares, the change should not be more than 5°C. This estimate does not contradict N.S. Kaminer's result [61] obtained from the data of continous recording of rigid component of cosmic rays during 1955-56.

While investigating the effect of small chromospheric flares on solar daily variation of neutron component (on the basis of the observational data obtained of Yakutsk, Resolute and Sulfur stations), G.V. Skripin et al. [70] did not observe the effect of small flares within the limits of experimental error. This result is particularly important and contradicts the conclusions drawn by B.M. Vladimirskii and A.K. Pankratov [24] and by Wilson and Nehra [22].

Increases in the intensity of cosmic rays, not directly related to the observed chromospheric flares, were detected by L.I. Dorman et al. [71]. Data of two hill stations -- Climax and Sulfur (cut-off rigidity being 2.9 and 0.97 Gv respectively)-- obtained during the IGY were analyzed for an indication of this effect. In all, 41 events were selected and it was shown that the increases during these events are not merely statistical fluctuations. Average curves, obtained by the superposed epoch method, show that there is a sudden increase, wide maximum for 4-6 hours and slow recovery of intensity. Corrections made for daily variation do not change the result. More than 50% of the effects of Climax station were observed around 12±2 hours local time. A comparison with the data on solar flares showed that, for most of the events, flares of class 2 or more are not observed for eight hours before the commencement of the sudden outburst. It is presumed that these outbursts are caused by chromospheric flares on the invisible side of the Sun although other causes, for example, sudden changes in the Earth's magnetosphere, might not be eliminated.

In all the above-mentioned works, small flares of cosmic rays were studied by statistically analyzing the data on a large number of solar flares. L.I. Dorman and E.V Kolomeets [72] made an attempt to study the effect of individual flares. In all, 10 flare events observed during June 16, 1957 - October 31, 1958 were analyzed. Data of neutron monitors after making correction for the barometric effect and the effect of first and the second harmonics of daily variation which was obtained from the data of the previous day, were used. A list of the flares and the results of the analysis are given in Table 6.1 ($\mathcal{E}_{min}$ is the geomagnetic cut-off energy). From the data available through the world network of stations which recorded the neutron component of the intensity of cosmic rays during 1959-64, V I. Ivanov and E.V. Kolomeets [73] analysed the effect of small chromospheric flares in cosmic rays. It was observed that decrease of the effect of the flares in the neutron component of cosmic rays from maximum to minimum solar

TABLE 6.1

Analysis of small individual flares [72]

Date of the flare	Effect on the Earth's surface, %	$\mathcal{E}_{\min}$, Gev	Effect in the stratosphere, %	$\mathcal{E}_{\min}$, Gev
July 17, 1957	0.8	2.5	2.6	1.6
August 21, 1957	1.6	2.4	5.1	1.6
September 20, 1957	0.8	2.6	5	1
October 29, 1957	No effect	2.5	No effect	1.6
March, 17, 1958	0.4	2.5	35	0.5
May 1, 1958	0.6	2.4	2	1.6
May 2, 1958	0.5	2.6	1.6	1.6
July 7, 1958	0.5	2.5	2100	0.2
August 16, 1958	0.6	2.4	22	1
October 31, 1958	0.5	2.5	19	1

activity is due to the less intensity of flares during the period of minimum solar activity. It was also shown that, during the period of minimum solar activity, the increase due to flares in the helioequatorial region and in the western half of the solar disk is more than that due to flares at higher latitudes and on the eastern half of the solar disk and this points out the existence of a regular magnetic field in the interplanetary space.

V.S. Smirnov [74] drew attention to the fact that the daily variation for Murmansk and Churchill stations averaged for quiet (with respect to geomagnetic field and Forbush effects) days with higher flare activity, reveals an additional morning increase for the period 1959-60. This increase is apparently caused by the propagation of particles of small flares of cosmic rays from a direction $\sim 60^o$ to the west of the Earth-Sun line. Absence of this increase during 1957-58 is related to the predominance, during this period, of the diffusion mechanism in the propagation of solar particles to the Earth. Daily variation, averaged for quiet days (amplitude of Forbush decrease more than 5%, K_p-index $\geqslant 30$) for 1957-60 period, reveals an additional increase at about 9 hours local time which may possibly be caused by particles propagating from a direction close to the Earth-Sun line.

The question of energy spectrum of particles giving rise to small flares of cosmic rays is considered in Section 10.

7. POSSIBILITY OF COLLECTIVE INVASION OF SOLAR COSMIC RAYS INTO THE EARTH'S MAGNETOSPHERE

While investigating the first phase of geomagnetic storm, Chapman and Ferraro [75] arrived at the preliminary conclusion that solar corpuscular beam can be geoeffective only if concentration of particles $n \geqslant 10^{-8}$ cm^{-3}. For the sake of simplicity, a cylindrical layer of plasma (solar particles) in the geomagnetic field was considered. It is natural that such an extremely simplified problem cannot reveal all the characteristic features of the real picture of interaction between solar plasma and geomagnetic field. With further assumptions, Ferraro [76] obtained an expression for the critical concentration of solar particles at which the electromagnetic interaction between them becomes negligibly small and they move in the geomagnetic field along Störmer orbits. This condition for crtical concentration is given by*)

$$\lambda \ll \left(\frac{3}{2\sqrt{2}}\right)^{1/2} \xi^{-3/2} l, \tag{7.1}$$

where ξ = 2.781 ; l is a constant of Strörmer's theory having the dimension of length:

$$l = \sqrt{\frac{eM}{mcv}}, \tag{7.2}$$

and λ is the screening length of plasma and it also has the dimensions of length and corresponds to the distance from the separating boundary at which the effect of magnetic field on plasma particles decreases by e times:

$$\lambda = \sqrt{\frac{mc^2}{8\pi n e^2}}. \tag{7.3}$$

The following notations are used in formulas (7. 2) and (7.3): m, v, e and n are respectively the mass, velocity, charge and concentration of particles; M is the Earth's magnetic moment and c, the velocity of light. The simplifying assumption that solar plasma consists of only one type of particles (protons) was made for deriving the formula (7. 1). Obviously, this assumption is fairly applicable to the case of solar cosmic rays. [1. 2].

From (7.1-(7.3) , we obtain an expression for the critical concentration n_* of solar particles (protons):

$$n_* = \frac{m^2 c^3 \xi^3}{6\sqrt{2}\pi e^3 M} v = 6{,}8 \cdot 10^{-15} \cdot v \,[\mathrm{cm}^{-3}] \tag{7.4}$$

(v is in cm/sec).

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*) *It should be mentioned that while deriving formula (7. 1), Ferraro [76] made an insignificant algebraic error which was pointed out by Chapman [77] and has been corrected here.*

In the case of isotopic radiation, by considering (7.4), the critical flux of particles (from directional hemispheres) is determined from the expression:

$$F_* = \pi I_* = \pi \cdot \frac{n_* v}{4\pi} = 1{,}7 \cdot 10^{-15} \cdot v^2 \, [\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1}] \qquad (7.5)$$

where I_* is the critical intensity of particles moving with a velocity v:

$$I_* = 5{,}4 \cdot 10^{-16} \cdot v^2 \, [\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1} \cdot \mathrm{sterad}^{-1}] \qquad (7.6)$$

The values of n_*, F_* and I_* for protons of different kinetic energies $\mathcal{E}_k$, calculated on the basis of formulas (7.4) - (7.6), are given in Table 7.1. The velocity is calculated from the relativistic relation

$$v(\varepsilon_k) = c\sqrt{1-\left(1+\frac{\varepsilon_k}{\varepsilon_0}\right)^{-2}}, \qquad (7.7)$$

where $\mathcal{E}_0$ is the potential energy of a proton.

Geoeffectiveness of some solar cosmic ray can be estimated on the basis of the obtained critical values. The differential spectrum of particles due to September 28, 1961 flare, recorded beyond the limits of the Earth's magnetosphere by the American satellite "Explorer-12" [1.23], can be approximated by the expression:

$$D(\mathcal{E}_k) = 2\ 10^3 .\ \mathcal{E}_k^{-3}\ [\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1} \cdot \mathrm{sterad}^{-1} \cdot \mathrm{Mev}^{-1}]$$

in the proton energy range of $\mathcal{E}_k$ =2-1000 Mev about 46 hours after the commencement of the flare. According to measurement taken by Brown and D'Arcy [78], the spectrum of particles in the same energy range during July 14-15, 1959 flare was much steeper and given by $D(\mathcal{E}_k) = 6 \times 10^{-12}\, \mathcal{E}_k^{-4.5}$ $[\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1} \cdot \mathrm{sterad}^{-1} \cdot \mathrm{Mev}^{-1}]$. Let us use the relations :

TABLE 7.1

$\mathcal{E}_k$, ev	v, cm/sec	n_*, cm^{-3}	F_*, cm^{-2} sec^{-1}	I_*, cm^{-2}, sec^{-1}, sterad^{-1}
1	1.38×10^6	9.4×10^{-9}	3.23×10^{-3}	1.03×10^{-3}
10	4.35×10^6	3×10^{-8}	3.23×10^{-2}	1.03×10^{-2}
10^2	1.38×10^7	9.4×10^{-8}	3.23×10^{-1}	1.03×10^{-1}
10^3	4.35×10^7	3×10^{-7}	3.23×10^0	1.03×10^0
10^4	1.38×10^8	9.4×10^{-7}	3.23×10^1	1.03×10^1
10^5	4.35×10^8	3×10^{-6}	3.23×10^2	1.03×10^2
10^6	1.38×10^9	9.4×10^{-6}	3.23×10^3	1.03×10^3
10^7	4.35×10^9	3.00×10^{-5}	3.23×10^4	1.03×10^4
10^8	1.24×10^{10}	8.45×10^{-5}	2.62×10^5	8.35×10^4
10^9	2.6×10^{10}	1.77×10^{-4}	1.15×10^6	3.67×10^5
10^{10}	2.88×10^{10}	1.96×10^{-4}	1.41×10^6	4.5×10^5

$$\left.\begin{aligned} n(\varepsilon_\kappa) &= \frac{4\pi}{v} D(\varepsilon_\kappa), \\ F(\varepsilon_\kappa) &= \pi D(\varepsilon_\kappa), \\ n(\varepsilon_1 \div \varepsilon_2) &= 4\pi \int_{\varepsilon_1}^{\varepsilon_2} \frac{1}{v} D(\varepsilon_\kappa)\, d\varepsilon_\kappa, \\ F(\varepsilon_1 \div \varepsilon_2) &= \pi \int_{\varepsilon_1}^{\varepsilon_2} D(\varepsilon_\kappa)\, d\varepsilon_\kappa. \end{aligned}\right\} \tag{7.8}$$

Here, it may be noted, that we can also use an approximate expression for the velocity in the above-mentioned energy range ($\mathcal{E}_k$ = 100-500 Mev) in place of (7.7):

$$v \approx \sqrt{\frac{2\varepsilon_\kappa}{m}} \approx 1{,}38 \cdot 10^9 \sqrt{\varepsilon_\kappa}\,[\text{cm. sec}^{-1}] \tag{7.9}$$

where $\mathcal{E}_k$ is expressed in Mev. The results of calculation obtained by L. I. Miroshnichenko for n($\mathcal{E}_k$) and F ($\mathcal{E}_k$), with the help of formulas (7. 8) and (7. 9) , are given in Table 7. 2

By comparing Tables 7. 1 and 7. 2, it can be concluded that the September 28, 1961 solar cosmic flare was not geo-effective whereas the July 14-15, 1959 flare could give a geomagnetic effect if this effect is considered to be due to the cumulative action of solar cosmic rays on the geomagnetic field (for example, the effect due to a proton beam of $\mathcal{E}_k$ = 100-400 Mev.) . A comparison of Tables 7. 1 and 7. 2 with the curves of Fig. 7. 1, taken from the work of Obayashi and Hakura [80], also leads to the same conclusion (also see the work [81] of the same authors)*.

Fig. 7. 1 shows the integral energy spectra of solar particles, obtained by different authors for different energy ranges: 1 - thermal particles of interplanetary plasma; 2- particles of corpuscular beam (for details of curves 1 and 2,

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* *Some deviations in the values of F_* in Fig. 7. 1 and Table 7. 1 can be explained by the fact that the calculations [81] were done by assuming that $\lambda = 1$ whereas critical values in Table 7. 1 were obtained in [79] on the basis of a more accurate relation (7. 1).*

TABLE 7.2

Date of the flare	$\mathcal{E}_k = 100$ Mev		$\mathcal{E}_k = 100 + 400$ Mev	
	n, cm^{-3}	F, cm^{-2}, sec^{-1}	n, cm^{-3}	F, cm^{-2}, sec^{-1}
July 14-15, 1959	6.05×10^{-6}	1.88×10^{4}	1.37×10^{-4}	5.4×10^{5}
September 28, 1961	2.02×10^{-12}	6.28×10^{-3}	7.3×10^{-10}	3.14×10^{-1}

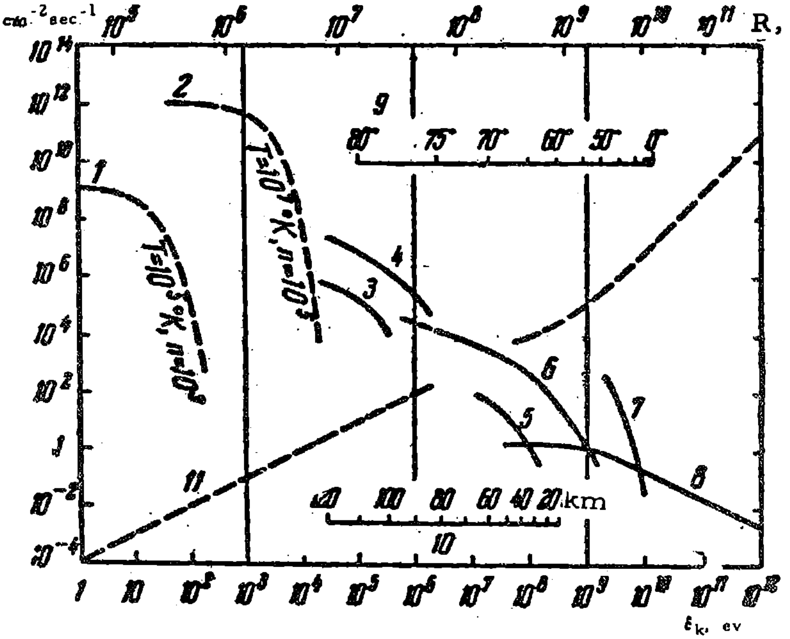

Fig. 7.1. Integral energy spectrum of solar corpuscular radiation [81]. 1,2,11 - calculated curves; 3-8 - experimental curves; 9 - scale of cut-off geomagnetic latitudes; 10 - altitude scale for penetration of protons in the Earth's atmosphere.

see the work of Obayshi and Hakura [87]);3 and 4 - particles giving rise to polar aurora (measurements by Van Allen [82] respectively); 5- particles, giving rise to absorption of radio waves in polar caps, on the basis of the data of Anderson et al. [84]; 6- spectrum of solar cosmic rays due to February 23, 1956 flare in the nonrelativistic region, according to the measurements of Van Allen and Winckler [85]; 7-spectrum of relativistic particles due to the same flare, measured by Meyer et al. [1. 4]; 8-spectrum of galactic cosmic rays obtained by Van Allen and Singer [86]. Scale of cut-off geomagnetic latitudes (9), scale of altitude for penetration of protons in the Earth's atmosphere (10) and the limit of freedom of protons during their motion in the geomagnetic field (curve 11 calculated in [81] by assuming that $\lambda = \ell$) are also shown.

On the other hand, it is possible to estimate by the following equation the intensity of energy contained in solar cosmic rays due to the July 14-15, 1959 flare in the energy range of 100-400 Mev:

$$w = \int_{100}^{400} \frac{4\pi}{v} \cdot 6 \cdot 10^{12} \varepsilon_k^{-4,5} \varepsilon_k \, d\varepsilon_k = 2{,}9 \cdot 10^{-8} \, [\mathrm{erg.\,cm}^{-3}]$$

This intensity of energy corresponds to the magnetic field of intensity H=8.55 x 10 gauss. By extending the spectrum right up to $\mathcal{E}_k \sim 10$ Mev, we get $w \approx 2.9 \times 10^{-5}$ erg. cm^{-3}. and $H = 2.7 \times 10^{-3}$ gauss. The geomagnetic field was approximated in Chapman's work [77] and is given by the expression $H = H_o \, (r_E/Z)^3$ for $Z > r_E$ where r_E is the Earth's radius, $H_o = 0.3$ gauss is the intensity of field at the equator and Z, is the distance from the center of the Earth in the equatorial plane. From this, the distance from the center of the Earth which could be covered by solar particles of July 14-15, 1959 flare is $Z = 7r_E$ at $H = 8.55 \times 10^{-4}$ gauss. Thus, considering from the data of Ness et al. [IV. 13] that the Earth's quiet magnetosphere occupies a volume with radius $\sim 10 \, r_E$, it can be assumed that solar cosmic rays in some cases collectively invade the magnetosphere to a considerable depth.

Such an invasion must give rise to disturbances in the magnetic field and possibly to polar auroras and other ionospheric effects at high geomagnetic latitudes ($> 60^o$) while the disturbance in the magnetic field must have a significant effect at distances $Z > 7 \, r_E$. Such phenomena during cosmic ray flares have not been observed up to this time. This fact can apparently be explained on the basis of A. S. Dvoryashin's assumption [14] that the steep energy spectrum of particles with $\mathcal{E} < 1$Gev, obtained from stratospheric observations, cannot be extended to low energies (~ 10 Mev) with the same angle of inclination and because of this, the beam of protons in this region must be described by a spectrum having sufficiently low index. It is actually confirmed for a number of flares by the data from stratorspheric and direct rocket measurements [1.2]. However, the obtained values of July 1959 events facilitate the assumption that some of the geophysical phenomena during this period could be caused by the intense beam of solar cosmic rays of medium energy (100-400 Mev). It is very difficult to verify this assumption due to the presence of a large number of geophysical effects in the middle of July 1959 and they are usually explained by superposition of many solar corpuscular beams. Thus, the question under reference requires further investigations.

CHAPTER III

ENERGY SPECTRUM, NUCLEAR COMPOSITION AND TIME VARIATIONS OF SOLAR COSMIC RAYS

The characteristic features of the spectrum and composition of solar cosmic rays and their time variations are considered in this Chapter on the basis of the data obtained from ground, stratospheric and extra-terrestrial measurements. Much attention has been paid to the effects of anisotropy of solar particles and to their displacement in the traps of corpuscular beams. The possibility of accumulation of low-energy particles in the solar system is considered and the theory and method of studying isotopic composition of solar particles is described. The effects of luminescence of the Moon and the Mercury under the action of solar corpuscular radiation are mentioned. The question of the shape of the spectrum and its other simple parameters occupies the main place in this Chapter.

8. ENERGY SPECTRUM

8.1 Pecularities of the spectrum. Till now, a large number of peculiarities in the spectrum of solar cosmic rays have been established. However its interpretation has proved to be ambiguous and contradictory.

1. The lower limit of the spectrum of solar cosmic rays is tentative and determined by the ratio of energy densities of solar cosmic rays and magnetic fields in which the particles propagate (local fields of the Sun's active regions, interplanetary and geomagnetic fields). If the density of energy contained in the solar particles becomes more than that of the magnetic field, these particles should be considered as a conductive gas. During the flare of July 14-15, 1959, solar particles with $\mathcal{E}_k$ = 100-400 Mev had such a high energy density ($\sim 3 \times 10^{-8}$ erg/cm^3) that they could collectively overcome the field with H $\lesssim 10^{-3}$ gauss (see Section 7). For most of the flares, the lower limit of the spectrum apparently lies in the region $\mathcal{E}_k = 10^5 - 10^6$ ev.

For example, during the flare of September 28, 1961, the spectrum of solar cosmic rays in the interplanetary space was measured by Bryant et al. [I. 23] right up to $\mathcal{E}_k \sim 1$ Mev.

2. The upper limits of the spectrum is determined by the possibility of retaining the accelerated particles in the source. If it is assumed that the Sun's supercorona of radius $5x10^{12}$ cm is the source and that $H \sim 10^{-4}$ gauss, is the intensity of irregularities of the field, the upper limit of the energy of particles held in the trap will be equal to $1.5x10^{11}$ ev. Relativistic solar particles with $\mathcal{E}_k \sim 2x10^{10}$ ev. were recorded during the most powerful of all the observed flares (February 23, 1956). Strictly speaking, the upper limit cannot be correctly determined experimentally due to large steepness of the spectrum of solar particles at high energies.

3. The inclination of the spectrum at energies of the order of a few hundred Mev depends on the state of the interplanetary medium. As shown by A. V. Charakhch'yan and T. N. Charakhch'yan [1], the index of differential spectrum γ in the absence of solar corpuscular beam is equal to 3 and is approximately the same for various flares. On the other hand, if the particles having the abovementioned energy move in the trap of the corpuscular beam, $\gamma=6$ and the spectrum mainly changes in the region $\mathcal{E}_k \lesssim 200$ Mev.

4. If the energy is more than a few hundred Mev, the spectrum becomes discontinuous and the index, according to A. N. Charakhch'yan and T. N. Charakhch'yan [2], increases up to $\gamma \approx 5\text{-}6$. The point of discontinuity can be different for different flares. This conclusion is drawn from the fact that there exists no proportionality between the amplitudes of outburst in the stratosphere and at sea level (i. e., in different energy ranges) for different flares. It should be mentioned that this proportionality is not at all possible for an individual flare since the spectral curve of solar cosmic rays at the Earth's orbit is practically not parallel to the corresponding curve for galactic particles.

5. Cosmic rays propagating to the Earth directly from the Sun in the initial phase of a flare have more rigid spectrum

than the scattered particles. Moreover, the spectrum of scattered particles as a rule softens with the passage of time*.

The authors in references [1, 2] assume that these pecularities of the spectrum are related to the phenomena of generation of cosmic rays on the Sun. The energy range of the particles, generated by the Sun, is apparently limited on the high side of energies but this limitation (i.e., the position of discontinuity in the spectrum) in specific cases is found to be different. In view of this, the existence of only one acceleration mechanism for high- and low-energy particles becomes doubtful. Experimental data on the spectra of protons, α -particles and nuclei of M group, expressed in terms of their kinetic energy, point out a similarity in these spectra. According to [2], the charge spectra of particles, generated on the Sun, are not constant from which it follows that there is apparently no definite relation between the nuclear composition of accelerated particles and the abundance of elements in the solar atmosphere. This conclusion, however, contradicts the results of other workers (see Section 9).

On the other hand, numerous observations show that, to the first approximation, the spectra of solar particles slightly depend upon the different parameters defining chromospheric flares (i.e. area, size, duration, position on the Sun, nature of visible movements, etc.). Thus, it is natural to consider that consistency of the spectrum of different flares is in some way, the general property of the dynamics of magnetized plasma and of thermodynamics of the gas of cosmic rays. As a matter of fact, as shown by S.I. Syrovatskii [3], the spectrum of solar cosmic rays can be obtained from general thermodynamical considerations without referring to specific values of the parameters of the acceleration mechanism.

First of all, it is appropriate to assume that a cavity, occupied by fast particles and retained by the pressure of external magnetic field, is formed as a result of an acceleration process in the solar atmosphere. At sufficiently high pressure of these particles and in the case of slow dissipation of their energy, the retaining magnetic field may be ruptured and the contents of the cavity will be ejected into the space about the Sun. In that case, considering the external pressure caused by the strong magnetic field of the spots, to be practically constant, it is possible to use the thermodynamical relation

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* *V.I. Ivanov and E.V. Kolomeets [165] showed that differential energy spectrum of solar cosmic rays in the range 1-8 Gev softens with a decrease in the solar activity:* $\gamma = 1.8$ *at the maximum and* $\gamma = 3.5$ *at the minimum. The upper limit of the spectrum changed from 8 to 2.5 Gev during 1957-64. There is no definite law in the region of energies* $\lesssim 1$ *Gev (as is evident from analysis of flares that were recorded at the Earth, in the stratosphere and in the interplanetary space).*

$$dW = \bar{\varepsilon}_\kappa dN, \tag{8.1}$$

where W is the thermal function of the system, N is the number of accelerated particles and ε_κ is the average kinetic energy of a particle in the cavity. The existence of a thermal function for the cavity points out that the system is not insulated: average energy of particles in the cavity increases with their exit due to the work done by the external pressure.

Cosmic rays can be considered as an ideal gas with constant ratio γ of heat capacities. Then

$$W = \gamma\varepsilon = \gamma N \bar{\varepsilon}_\kappa, \tag{8.2}$$

where ε is the total energy of particles in the cavity. Putting (8.2) in (8.1), we get

$$\frac{dN}{N} = -\frac{\gamma}{\gamma-1}\frac{d\bar{\varepsilon}_\kappa}{\bar{\varepsilon}_\kappa}, \tag{8.3}$$

from which we get the following relation between the number of particles in the cavity and their average energy:

$$N = \mathrm{const} \cdot \bar{\varepsilon}_\kappa^{-\gamma/(\gamma-1)}. \tag{8.4}$$

Therefore spectrum of the particle coming out of the cavity will be of the form

$$\delta D(\varepsilon_\kappa) d\varepsilon_\kappa = -dN = \mathrm{const} \cdot \varepsilon_\kappa^{-(2\gamma-1)/(\gamma-1)}, \tag{8.5}$$

where the average energy has been replaced by the actual energy which, according to [3], is valid from the known general concepts about the nature of the generation spectrum. As was shown by V. L. Ginzburg and S. I. Syrovatskii [4], for strictly steady acceleration between adjoining parallel walls, $\gamma = 3$ in the non-relativistic case and $\gamma = 2$ in the relativistic case. For betatron acceleration, $\gamma = 2$ and $\gamma = 3/2$ respectively. These values are obtained by assuming that the energy is transferred only to one (in the case of walls) or two (in the case of betatron acceleration) degrees of freedom of a particle. However, in the case of not absolutely parallel walls and also due to scattering at irregularities of the magnetic field, all the degrees of freedom of the particle, in the long run, become equally justified. Therefore, as in the case of an ideal gas, $\gamma = 5/3$ in the nonrelativistic case and $\gamma = 4/3$ in the relativistic case. At these values of γ, the spectrum of solar cosmic rays, as given by equation (8.5), must be a power function with an index of 3.5 in the region of nonrelativistic energies and 5 in the ultrarelativistic region. In general, this type of spectrum is in agreement with the observations. On the other hand, in some cases, the spectral index is $\geqslant 5$ even in the region of comparatively low energies ($\mathcal{E}_k \sim 100$-300 Mev for protons). Moreover, the conclusions [1-3] do not eliminate the difficulties related to the explanation of the change of spectrum with time.

There are other possibilities as well for explaining these facts. First of all, different types of losses in the acceleration region (radiation, viscous and Joule dissipation) as well as the possible variations in the external magnetic field due to compression of the cavity, in which the particles are compressed, must lead to softening of the spectrum. Further, if it is assumed that the accelerated particles from flares, preceeding the effective flare, accumulate in some region, then, as shown by A.A. Stepanyan and B.M. Vladimirskii [5], the relation between high-energy and low-energy components will be practically absent. Moreover, in the process of propagation of particles in the interplanetary space, the spectrum is considerably transformed owing to the dependence of diffusion coefficient on the energy of particles (see Chapter IV).

8.2 Form of the spectrum. In the recent past, spectra of solar cosmic rays in the energy range from a few Mev to tens of Gev were measured by different methods not only for protons but also for nuclei with $Z \geqslant 2$.

Owing to different measurement procedures used in different energy intervals, it becomes necessary to coordinate the results of different measurements and to find a simple form of the spectrum and its changes with the passage of time. Usually, differential spectrum is written in the form of a power function of rigidity or kinetic energy of the particle:

$$\frac{dI}{dR} = K_1 R^{-\gamma_1}, \qquad (8.6)$$

$$\frac{dI}{d\varepsilon_k} = K_2 \varepsilon_k^{-\gamma_2}, \qquad (8.7)$$

where γ_1 and γ_2 are simultaneously the functions of rigidity (or energy) and time. It is known from the experiment that γ_1 and γ_2 have small values at low ε_k or R where the spectrum is observed to have a "bend". Moreover, γ_1 and γ_2 usually increase with time which leads to softening of the spectrum. In a number of works, it was also shown that solar protons and particles have similar shape and rigidity spectra. It led Freier and Webber [6, 7] to conclude that rigidity can serve as a fundamental parameter for understanding the process of the origin of spectrum at the Sun and for interpreting the above-mentioned data near the Earth.

Since the range of rigidities or energies covered by one measurement is usually very narrow, the spectrum of solar particles can be written to a sufficient degree of accuracy in the form of a power function of rigidity or energy with constant index γ. This representation will no more be satisfactory if one considers the total range of rigidities or energies although it can, of course, be assumed that the indices γ_1 and γ_2 depend on the rigidity or energy. For an accurate description of the spectrum, it is necessary to coordinate the results of measurements obtained with the help of rockets, satellites and riometers in the range of low energies (1-50 Mev), with the data of balloon measurements taken with the help of emulsions, counters and ionization chambers at medium energies (70-500 Mev) and also with the results of ground measurements in the region $\varepsilon_k > 500$ Mev. With this end in view, it is necessary to correctly know the absolute sensitivity of these detectors to different regions of the primary spectrum. On the other hand, the determination of sensitivity requires certain assumptions about the form of the primary spectrum. Since the power spectrum of primary radiation has an index which is simultaneously a function of the energy (or rigidity) and time, one cannot be sure of the accuracy of extrapolation in these cases to different energy regions covering many types of measurements. In this case, the determination of spectra is complicated by nonlinear calculations.

Taking these difficulties into consideration, Freier and Webber [6] made a thorough study of the data on many flares and arrived at the conclusion that the spectrum of solar particles can be best expressed by a single-parameter exponential function:

$$\frac{dI}{dR} = \left[\frac{dI}{dR}(t)\right]_0 e^{-R/R_0(t)}, \qquad (8.8)$$

where $R_0(t)$ is the rigidity characteristic which for a given flare depends only on time. Its value and time dependence change from flare to flare. As confirmed by the authors [6], the equation (8.8) is applicable at all rigidities only at a time which, after the commencement of the flare considerably exceeds the time of direct propagation of particles from the Sun to the Earth. In the case of the spectrum of type given by equation (8.8), it is no more necessary to artificially "bend" it at low energies since R_0 does not depend on R but the result is found to be the same as in the case of "bent" power spectrum. The relation (8.8) makes it possible to forecast the intensity of low-energy particles which can later on be related to characteristics of the corresponding magnetic storm. On the basis of equation (8.8), the curves of time variation can easily be interpreted by the observational data obtained with the help of different detectors.

By using all the available observational data of Minnesota complex, Freier and Webber [6] determined the spectra of protons for 53 different instants of time during 16 different flare events. Those cases where the measurements were obtained with the help of emulsions, it was possible to determine the flux of α-particles and the ratio of the flux of protons to that of α-particles. The results of this investigation are shown in Table 8.1.

In accordance with the equation (8.8), the integral rigidity spectrum will be of the form

$$I(>R) = I_0 e^{-R/R_0}. \tag{8.9}$$

where R_0 has the same value for protons and α -particles but I_0 can have different values. It should be mentioned that the counter measurements usually give integral flux of particles whereas emulsion measurements give differential flux.

In order to understand the meaning of parameters I_0 and R_0, the authors [6] studied their time variation for some flares. The measured values of I_0 and R_0 are shown in Fig. 8.1 for the period November 12-16, 1960 and July 11-21, 1961. The times of solar flares, fade-outs and sudden commencements of geomagnetic storms are shown by arrows. The parameter I_0 is the global intensity of solar particles near the Earth free from the possible geomagnetic effects. Calculation of I_0 requires extrapolation of the measured spectrum to the region of low rigidities. In order to determine the time variation of I_0, the authors [6] used riometric data of high-latitude stations Longyearbyen and College which have a cut-off rigidity approximately equal to zero. This procedure is not devoid of errors since the sensitivity of the riometer decreases in the region $\mathcal{E}_k < 15$-20 Mev.

In order to study the relation between I_0 and R_0 and the characteristics of interplanetary fields in detail, Freier and Webber plotted the integral spectra of solar protons (Fig. 8.2), obtained for the interplanetary space at the time of maximum I_0 for flares on November 12 and 15, 1960 and on July 12 and 18, 1961, right up to 2 Mev ($R \approx 60$ Mv). Fig. 8.2 also shows the flux and intensity of energy ($1/2\ nmv^2 = H^2/8\pi$) for a mono-energy beam of solar protons. The crosshatched regions belong to the plasma front causing geomagnetic storm (1) and the quiet interplanetary plasma (2). The velocity of low-energy protons of the plasma, their flux and the number density of particles are also shown in the Fig. The cited values of these parameters were obtained on the basis of latest available data on time of propagation of plasma from the Sun to the Earth and the data considered are those of direct measurements of Bridge et al. [17] on the spectrum and flux of plasma particles and the results of Sonett's measurements [18] on the limit of the geomagnetic field.

TABLE 8.1

Integral exponential spectra of solar particles

Date of solar flare	Time of optical maximum, UT	Time of measurement, UT		I_0, proton x cm^{-2} sec^{-1} sterad^{-1}	R_0, Mv	Type of the detector	Literature	Ratio p.α
1	2	3		4	5	6	7	8
February 23, 1956	03.42	February 23	19.30	140	300	TA	[1.11]	
March 23, 1958	10.05	March 26	14.00	640	80	CA, E	[8]	1.0±0.5
			18.15					
May 10, 1959	21.18	May 12	05.00	3 x 10^3	65	CA	[9]	
			05.20					
			09.15	18 x 10^3	70	E	[10]	
			09.15					
			13.35	4.1 x 10^3	70	E	[10]	1.0±0.5
			13.35					
			17.50	2.8 x 10^3	66	E	[10]	1.0±0.5
July 10, 1959	02.22	July 11	07.55	7.8 x 10^3	90	E	[11]	1.4±0.3
			16.25					
		July 12	12.25	2.1 x 10^3	90	E	[11]	5.0±1.0
			23.45					
July 14, 1959	03.49	July 15	13.30	3.5 x 10^4	68	E	[10]	1.0±0.5
			15.55					
July 16, 1959	21.45	July 17	12.00	3.2 x 10^3	125	CA	[1.65]	
			15.55	1.1 x 10^3	113	E	[10]	1.0±0.5
			19.35					
		August 18	14.00	800	90	CA	[12]	
			13.50	2800	70	E	[10]	
			16.40					
		July 20	14.45	300	66	CA	[12]	
April 1, 1960	08.59	April 1	10.20	10	155	CA	[13]	
April 28, 1960	01.30	April 28	12.50	2.4	240	CA	[13]	
		April 29	03.00	1.9	150	CA	[13]	
April 26, 1960	02.20	April 24,	05.00	40	105	CA	[13]	
May 4, 1960	10.20	May 4	16.30	6.7	280	CA	[14]	
		May 5	17.00	5.8	235	E	[15]	≥ 50
September 3, 1960	01.10	September 3	09.00	42	225	CA	[16]	
			09.30					
			17.30	60	180	E	[1.81]	40
		September 4	16.50	26	150	E	[1.81]	30
			23.20					
			23.00	12	155	CA	*	

		September 6	04.00	7.2	120	CA	*	
		September 7	05.30	4.0	120	CA	*	
November 12, 1960	13.29	November 12	19.30	1100	280	CA	*	
			20.00	1250	240	CA	*	
		November 13	02.00	3400	185	CA	*	
November 12, 1960	13.29	November 13	08.00	3400	155	CA	*	
			13.05	3000	120	CA	*	
			18.30 •20.00	2800	95	E	[11]	1.0±0.5
			22.30	1000	105	CA	*	
		November 14	05.00	1000	95	CA	*	
November 15, 1960	02.21	November 15	05.00	250	375	CA	*	
			11.30	320	240	CA	*	
			10.30 12.30	285	175	E	[1.82]	1±0.5
			21.30	3300	120	CA	*	
		November 16	09.30	1000	100	CA	*	
			14.30 17.30	300	100	E	[1.82]	2±1
July 12, 1961	10.30	July 13	00.10	850	60	CA	*	
			09.00 16.20	5450	46	E	[10]	
		July 14	17.45	1200	45	CA	**	
July 18, 1961	10.10	July 18	15.35 17.50	500	160	E	[10]	6±1
			17.20	1000	150	CA	**	
			21.00 23.30	1100	135	E	[10]	6±1
			23.45	700	130	CA	**	
		July 19	03.00	430	125	CA	**	
			06.50	260	120	CA	**	
			20.00	210	100	CA	**	
		July 20	13.10	120	90	CA	**	
		July 21	02.00	100	90	CA	**	
		July 22	01.00	60	80	CA	**	
September 28, 1961	22.23	September 29	03.30	60	210	CA	*	

TA - Telescope counter; CA - Single counter; E - Photoemulsion; * - Winckler's unpublished data

** - Hofmann's unpublished data

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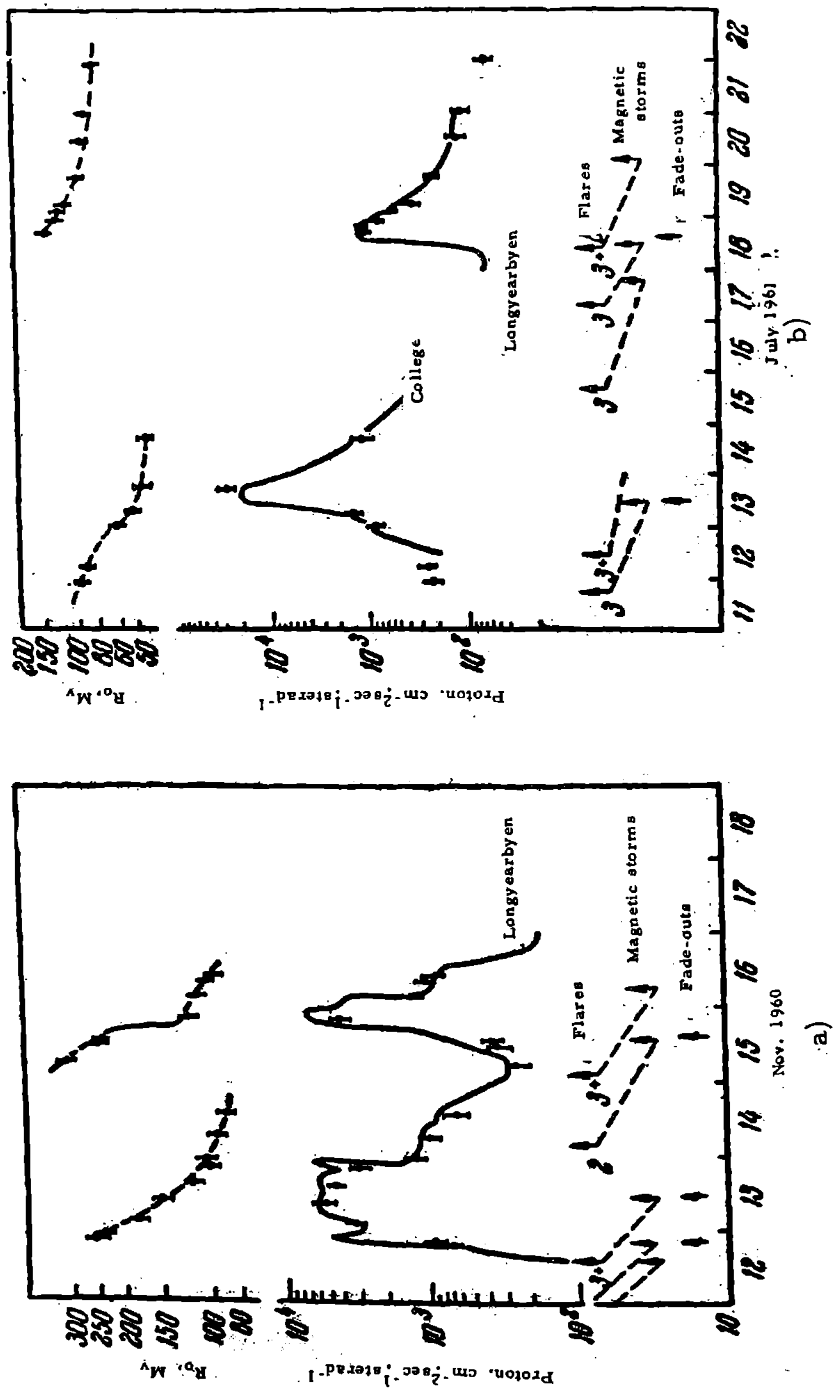
[1] In the text, the time UT has been expressed as a four digit number.



a)

b)

Fig. 8.1. Time variations of R_o and I_o [6].
a) during November 12-16, 1960; b) during July 11-21, 1961.

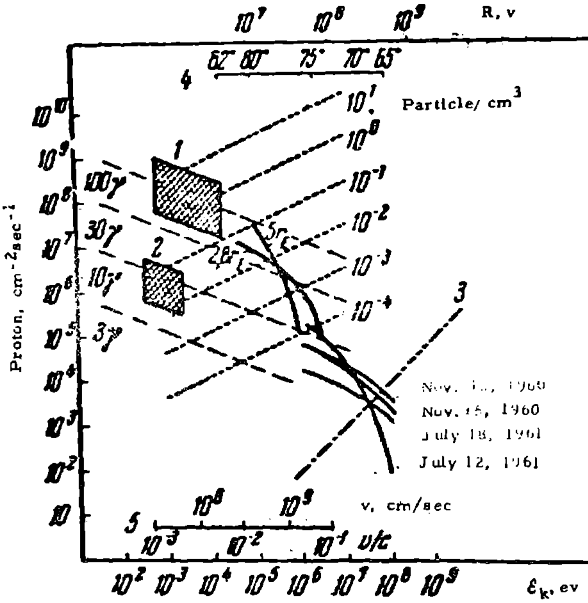


Fig. 8.2. Integral spectra of solar protons at the time of maximum intensity for flares on November 12 and 15, 1960 and on July 12 and 18, 1961 [6]. The crosshatched regions 1 and 2 belong to the disturbed and quiet interplanetary field respectively; 3-limit of freedom of protons during their movement in the geomagnetic field; 4 - scale of cut-off geomagnetic latitudes; 5 - velocity of interplanetary plasma particles. Spectra of protons at distances of 2.8 r_E and $5r_E$ are also shown.

The measured spectra of solar particles at the time of maximum N_0 for flares on November 12 and 15, 1960 and on July 12 and 18, 1961 give the same densities of energy for the "plasma" of cosmic rays as for the quiet interplanetary field. Therefore, the motion of solar particles will be significantly controlled by this field. The density of energy of low-energy plasma and magnetic fields, most probably, increases in the presence of a plasma of solar cosmic rays in the interplanetary space. As a result, plasma of cosmic rays apparently never predominates over the interplanetary field but is always controlled by it and the resultant motion is defined by the dynamics of interaction of these two types of plasma. Thus, the plasma of cosmic rays and the low-energy plasma, containing interplanetary fields, are closely related to each other. This fact is confirmed by Fig. 8.2 from which it is obvious that flares of cosmic rays having the steepest spectra and maximum intensities of low-energy particles are accompanied by strongest geomagnetic storms (for example, compare July 12 and 18, 1961 events).

Extrapolation of exponential spectra, corresponding to maximum intensity of solar cosmic rays to the region of low energies, does not provide large number of particles or intensity of energy sufficient for causing a magnetic storm. Therefore, it is not entirely eliminated that the spectrum of solar cosmic rays is the high-energy tail of thermal distribution, related to low-energy (thermal) plasma. In this case, there must be a transition region of energies (probably within the interval $\mathcal{E}_k$ = 100 kev- 2 Mev).

Many important results regarding this problem were obtained in August-September 1961 by Davis and Williamson [19] who measured the flux of trapped protons in the range $\mathcal{E}_k$ = 100 kev - 4.5 Mev at distances of 2-8 r_E. Typical proton spectra for distances of 2.8 and 5 r_E, shown in Fig. 8.2, can be described by an exponential with R_0 = 15 and 5 Mev respectively. It is possible that the particles measured by Davis and Williamson [19] belong to the spectrum, modified in the process of capture and subsequent movement (which leads to an increase in the steepness of the spectrum), of the plasma-front protons. The trapped protons can obviously be considered as remnant of the preceding plasma cloud. Owing to this, Freier and Webber [6] tried to obtain conformity of the measured values of R_0 and N_0 for trapped particles with the values expected for the characteristic of the strong magnetic storm on July 13, 1961. A detailed study of the spectra of solar protons in the critical range of energies between low-energy plasma and plasma of cosmic rays (for example, in the range $\mathcal{E}_k$ = 0.1-5 Mev) during magnetic storms will help in understanding the obviously close relation between these two components.

Similar problems have also been considered in Section 7 where much importance is given to the possibility of collective invasion of solar cosmic rays into the Earth's atmosphere.

In connection with the problem of exponential spectrum, Freier's results of emulsion measurements [10] on solar

α -particles and protons during the flares, observed on May 10, 1959, July 14 and 16, 1959 and on July 12 and 18, 1961 are of great interest. Rigidity spectra of both types of particles in these cases have exponential nature. The fluxes of particles at different times were measured during each flare. For these five flares, it has become possible to determine the ratio of the flux of protons to that of α -particles at the same rigidity in six cases.

The results of measurements on these five flare events are included in Table 8. 1. All the measurements were obtained with the aid of ballons over Minneapolis (cut-off rigidity in the case of quiet geomagnetic field, according to Quenby and Wenk [I. 33], is equal to 1. 34 Gv) or over Churchill (R $\sim$ 0. 18 Gv).

The spectra obtained on the basis of emulsion measurements of protons and α -particles on May 12, 1959 are shown in Fig. 8. 3 in semilogarithmic scale. It is obvious that, at low rigidities, the flux of α -particles measured over Minneapolis is less than that expected from the exponential form of the spectrum. A similar bend in the spectrum was observed on July 16, 1959 (for α -particles) and July 18, 1961 (for protons and α -particles) [10].

Freier [11], Earl [12] and Bhavsar [1. 77] showed that the threshold rigidity at Minneapolis during quiet periods goes up to 1. 20 Gv while during geomagnetic disturbances, it decreases to 0. 3 Gv. Moreover, it was found that the cut-off threshold is not very sharp during cosmic-ray flares. Such an effect was observed during similar balloon flights over Churchill and Minneapolis. Consequently, the bend in the spectrum, sometimes observed over Minneapolis, can explain the change in the threshold rigidity. In this case, the rigidity at which the spectrum starts bending serves as a measure of the cut-off rigidity at the observation point during the flare.

It is important to mention that proton and α -particle spectra near the Earth are found to be modified, with respect to emission spectra, in the process of propagation in the interplanetary space. But in the opinion of Freier and Webber [6], this process changes R_0 but does not change the exponential nature of the spectrum.

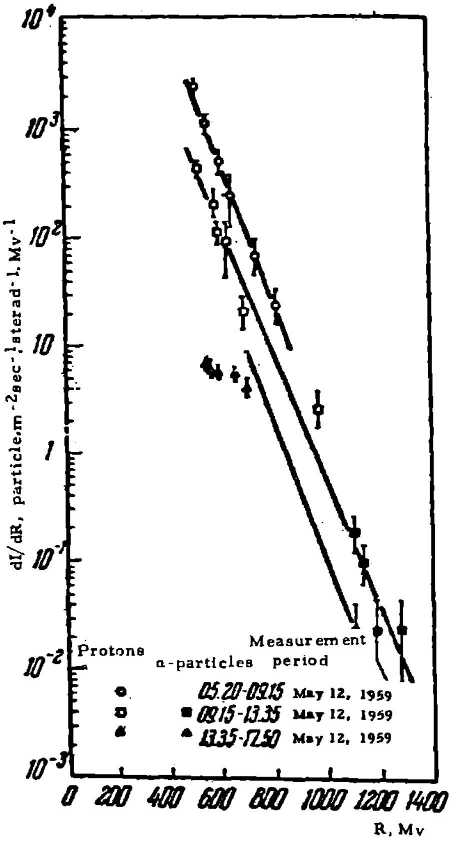


Fig. 8. 3. Differential rigidity spectra for solar protons and α-particles on the basis of measurements taken on May 12, 1959 [10].

Interesting results on the measurement of the spectrum of solar α-particles were obtained by Yates [1, 14] during November 12-13, 1960 flare with the aid of scintillation telescope counter and Cerenkov counter installed on balloons. As a matter of fact, this was the first time when it was shown by direct measurements that the Sun actually generates relativistic α-particles (>560 Mev/nucleon). Corrections for the background, nuclear reactions in the counter's material and for the mass of the residual atmosphere over the detector were made for the data obtained. The values of the total flux of α-particles at the boundary of the atmosphere obtained on November 13, 1960 along with the corresponding data on other flares are given in Table 8.2

TABLE 8.2

Intensity of α-particles at the boundary of the atmosphere ($m^{-2}.sec^{-1}.sterad^{-1}$)

Date of the flight	$2.3 < R < 2.9$ Gv	$R > 2.9$ Gv	$R > 2.3$ Gv
July 13, 1959	23 ± 6	110 ± 20	133 ± 24
August 19, 1959			143 ± 23
May 5, 1960	25 ± 5	124 ± 17	149 ± 19
November 13, 1960	43 ± 10	148^{+31}_{-27}	191^{+39}_{-33}
November 20, 1960	16 ± 3	122 ± 14	138 ± 14

In order to determine the flux of solar α -particles, it is necessary to consider the background flux caused by α-particles of galactic cosmic rays. With this aim, Yates [1.14] made use of the correlation between the counting rate of neutron monitor at Climax and the flux of α -particles measured by Meyer [20] for the period September 1957-July 1959. This dependence for α -particles with R $\gtrsim$ 2.3 Gv (threshold rigidity for Climax is 2.91 Gv) is shown in Fig. 8.4. Considering the counting rate of neutron monitor at Climax (2888 pulses/2 hours) on the quiet day of November 11, 1960, from Fig. 8.4 we find that the intensity of galactic α-particles is equal to 156±6 m^{-2} sec^{-1} $sterad^{-1}$. A similar estimate for November 13, 1960 shows an intensity of 134±4 m^{-2} sec^{-1} $sterad^{-1}$. A comparison of these values with the data given in Table 8.2 shows that the intensity of relativistic α -particles of R $\gtrsim$ 2.3 Gv during the period 1015-1915 UT on November 13, 1960 was more than that of galactic α -particles during the quiet period (134 ± 4 m^{2}.sec^{-1} $sterad^{-1}$ and also during disturbances (156 ± 6 m^{-2} sec^{-1} $sterad^{-1}$). It follows from this that the excess intensity of α -particles (55^{+31}_{-25} m^{-2}. sec^{-1}.$sterad^{-1}$) was caused by their injection from the Sun during November 12, 1960 flare event.

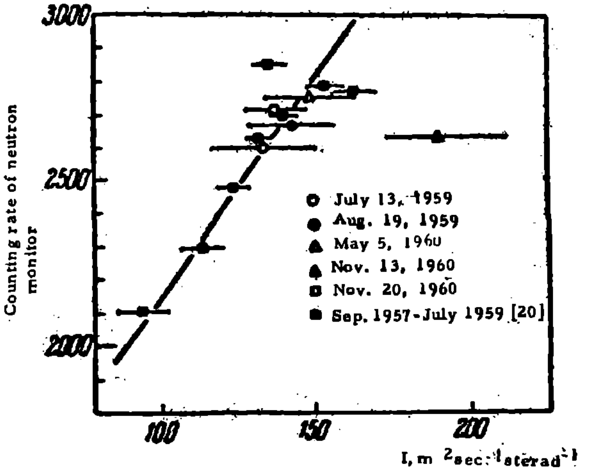


Fig. 8.4. Correlation between counting rate of neutron monitor at Climax and intensity of α-particles measured by Yates [I.14] and Meyer [20]. The straight line is drawn without considering November 13, 1960 data.

Two more experiments on determination of the flux and spectrum of α-particles with $\mathcal{E}_k \leq 120$ Mev/nucleon during approximately the same interval of time on November 13, 1960 were conducted by Ney and Stein [1.82] and Biswas et al. [21]. The results obtained in all the three experiments are compared in Figs. 8.5 and 8.6 in which are shown the differential spectra of solar α-particles according to the energy per nucleon and rigidity. Moreover, the rigidity scale in Fig. 8.6, a, is linear and in Fig. 8.6, b, it is logarithmic. It is obvious that Yates data [1.14] for relativistic α-particles are satisfactorily described by the spectrum of the type $\sim \mathcal{E}^{-4}$ or $\sim R^{-7}$ whereas the exponential rigidity spectrum, suggested by Freier and Webber [6] gives rise to sharp deviations (Fig. 8.6). In order to explain this deviation, Yates [1.14] suggested an interesting model of propagation of solar particles in the interplanetary space.

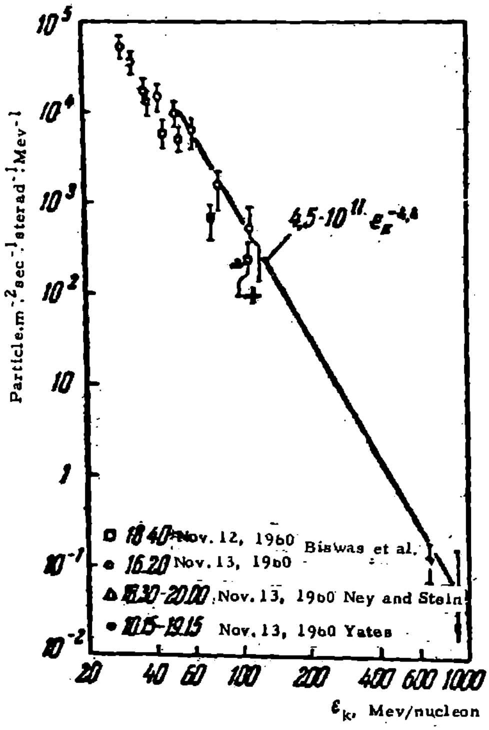


Fig. 8.5. The differential energy spectrum of solar α-particles according to the data obtained by various authors for the period November 12-13, 1960. The straight line corresponds to spectrum $\mathcal{E}^{-4.4}$.

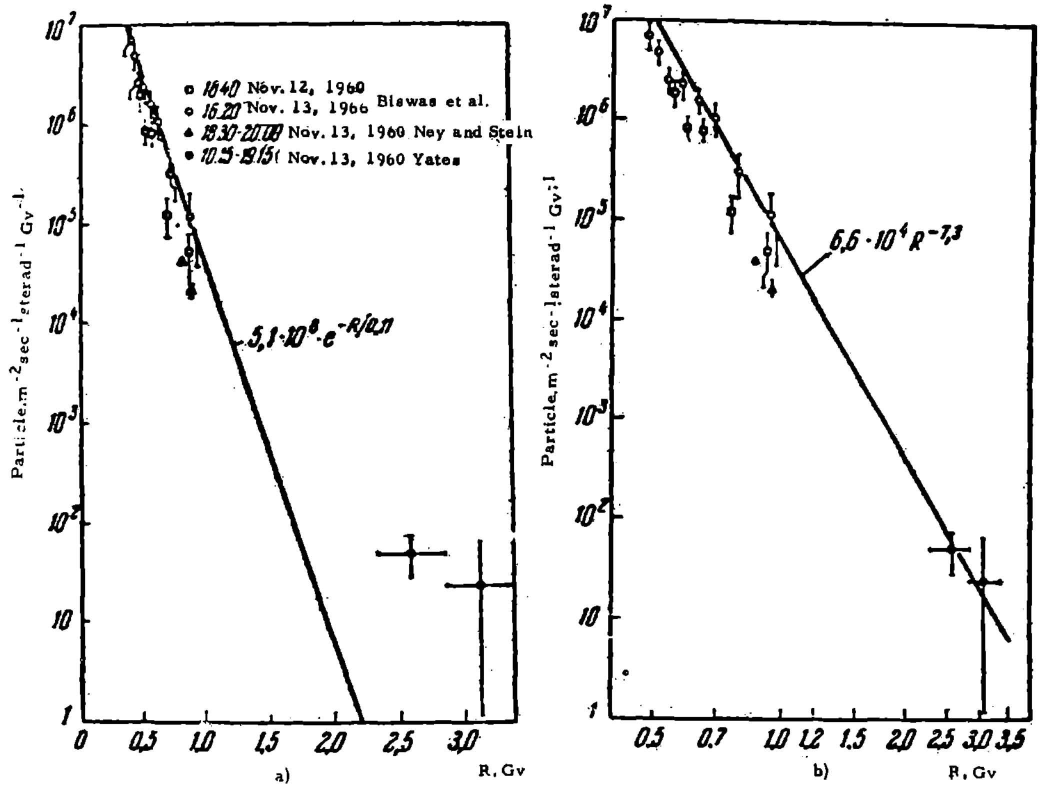


Fig. 8. 6. Differential rigidity spectrum of solar a*-particles as an exponential (a) and power (b) function.*

Two Forbush decreases in the intensity of cosmic rays were observed on the Earth during this period. These decreases commenced at 1930 UT on November 12, 1960 and at 1030 UT on November 13, 1960 respectively. At the commencement of the phenomenon, solar particles trapped in-between the two fronts, moving away from the Sun and which are related to Forbush decrease (I), not only got into the Galaxy but also filled up the region about the Sun (II) through the front close to the Sun, and because of this the number of α -particles in this region almost remained constant. About a day after the commencement of the flare, the fluxes of α-particles in the region in-between the "fronts" and in the region close to the Sun became approximately equal.

This contradicts the result obtained by Roederer et al. [22]. According to [22], a significant decrease in the flux of solar particles with $R \sim 1$ Gv was observed at about 1100 UT on November 13, 1960. In the opinion of Yates [I. 14], infiltration in the region II was more favorable for high-rigidity particles and this explains the increase in the flux of α-particles, with $R \gtrsim 2.3$ Gv, in the spectrum of solar cosmic rays after 1030 UT (i.e., in the region II). It follows from this that solar particles in the region I obviously had an exponential rigidity spectrum whereas their spectrum in the region II can be expressed as a power function of $\mathcal{E}_k$ or R.

Waddington and Freier [23] doubted the validity of results obtained by Yates [I. 14]. They showed that the higher values of intensity of α-particles in Yates measurements are due to instrumental errors: this can be observed by comparing the data with emulsion measurements. The excess intensity might be, in particular, caused by the recording of low-energy solar protons whose flux was exceptionally high on November 13, 1960. In reply, Yates [24] confirmed that pulses from slow protons could not have led to the observed effect and that the exponential rigidity spectrum might be most probably caused by modulation of the generation spectrum of α-particles during their propagation in the interplanetary space.

In this connection, it may be mentioned that the strongest arguments of Freier and Webber [6] in favor of exponential spectrum at high values of R were based on the data of November 15, 1960 flare event. Moreover, November 12-13, 1960 event, related to the presence of two magnetic "fronts" in the interplanetary space, should be obviously different from November 15, 1960 event. Actually, in the absence of front I, the particles in the region I would have been dispersed rapidly and lesser number of these particles would have entered the region II throgh the front II.

The differences in these two events were pointed out by Ogilwie and Bryant [25]. According to [25], the exponential rigidity spectrum does not correspond to observation data of November 12, 1960 because of relatively high flux of low-energy protons. The data, obtained on November 16, 1960 at 1951 UT (right up to $\mathcal{E} < 15$ Mev), are in agreement with the exponential spectrum (Fig. 8.7). This difference is apparently caused by the flux of low-energy protons propagating to the Earth on November 12, 1960 along with solar plasma which was responsible for the simultaneous geomagnetic disturbances. Rocket measurements were also made on November 16, 1960 during the magnetically quiet period.

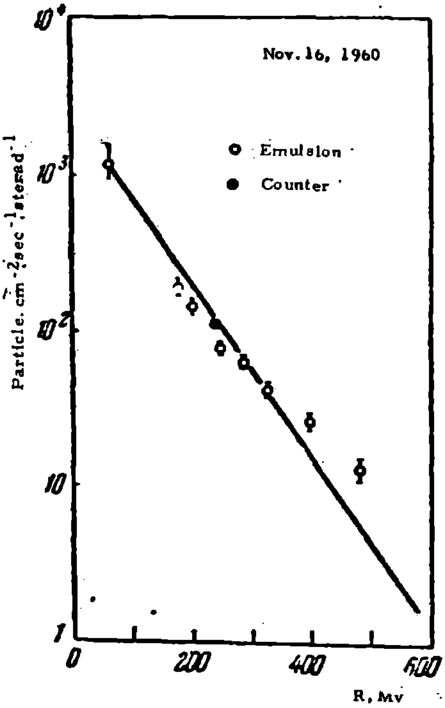


Fig. 8.7. Rigidity spectrum of solar particles at 1951 UT on November 16, 1960 based on the data of emulsion [28] and counter [83] measurements.

The data on some other flare events as well do not correspond to the exponential form of the spectrum. Fig. 8.8 shows the rigidity spectra of solar particles due to February 23, 1956 flare event at three different times. These curves are drawn in the semilogarithmic scale based on the spectra obtained by L.I. Dorman and L.I. Miroshnichenko [I. 36]. It may be noted that the February 23, 1956 flare also contradicts the assumption made by Freier and Webber [6] but this tendency is very much less due to the uncertainty in the position of experimental points along R-axis which, in its own turn, is caused by the insufficient number of stations which had recorded this flare.

More accurate results were recently obtained for September 28, 1961, November 10, 1961 and October 23, 1962 flare events. Based on the data of satellite measurements beyond the limits of the Earth's magnetosphere, Bryant et al. [I. 26] (for all the three flares) and L. I. Dorman and L. I. Miroshnichenko [IV. 64] (only for September 28, 1961 flare) independently determined the spectra of nonrelativistic solar protons ($\mathcal{E}_k \leq$ 500 Mev) at the time of their emission. These spectra, obtained on the basis of the diffusion theory (see Chapter IV) have a power function where the value of γ , for example for September 28, 1961 flare, is within the limits 1.7-2.0.

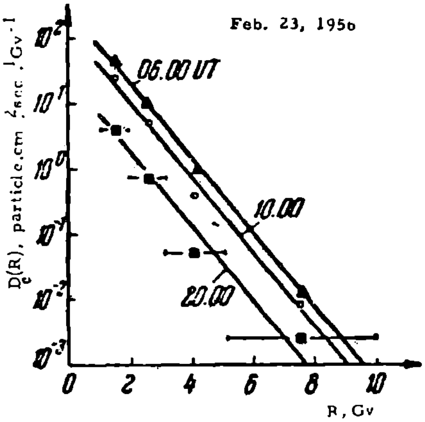


Fig. 8. 8. Differential rigidity spectra of solar particles at 0600, 1000 and 2000 UT on February 23, 1956 [I. 36]. The uncertainty in the position of points along R-axis which is same for all the three cases, is shown only for 2000 UT.

If a graph of the dependence of the number of emitted particles against their rigidity is plotted in semilogarithmic scale, we obtain the curves shown in Fig. 8. 9 (see [26, 27]). Although data on September 28, 1961 flare cover about 1/30th range of rigidities, it is obvious from Fig. 8. 9 that the shape of the emission spectrum for this flare (as well as for November 10, 1961 and October 23, 1962 flares) contradicts the assumption made by Freier and Webber [6]. It may be mentioned that the spectrum of some protons, observed by Bryant et al. [I. 23] near the Earth, 46 hours after the commencement of September 28, 1961 flare, had a power function $\sim \mathcal{E}^{-\gamma}$ where $\gamma \approx 3$ in the range $\mathcal{E}_k$ = 2-600 Mev.

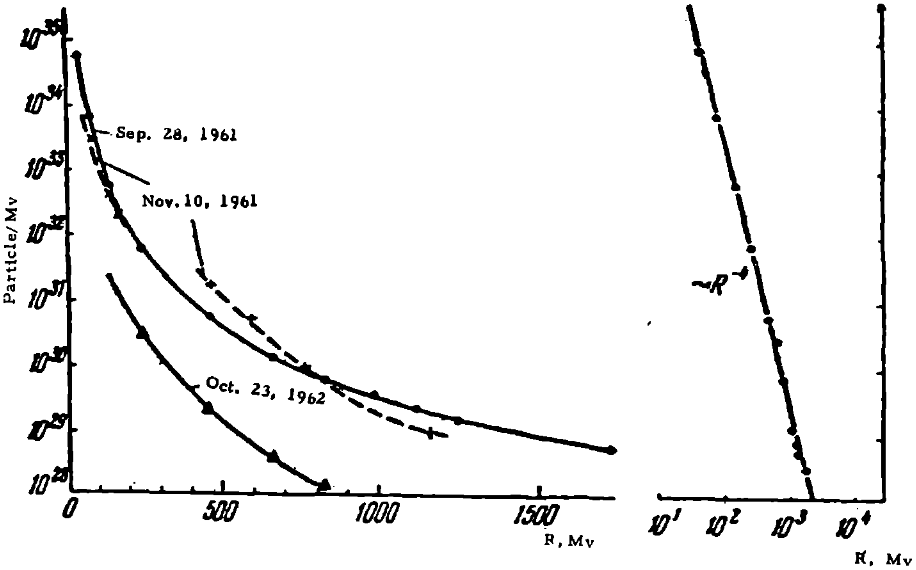


Fig. 8. 9. Differential rigidity spectra of solar particles at the moment of emission for September 28, 1961, November 10, 1961 and October 23, 1962 flares. Power rigidity spectrum of solar particles from September 28, 1961 flare at the time of emission is shown on the right [I. 26; IV. 64].

The rigidity spectrum of solar particles from September 28, 1961 flare at the time of emission, obtained on the basis of the results [I. 26; IV.64] is shown on the right in Fig. 8.9. It is obvious that, in accordance with the data of Fig. 14.33 taken from [IV. 28], the spectrum satisfactorily corresponds to the power function $\sim R^{-4}$.

Thus, neither the exponential rigidity spectrum nor any other form of the above-mentioned functions is suitable for describing the spectrum of solar cosmic rays in the region of low-rigidities ($R < 500$ Mv).

The emission spectra for February 23, 1956; May 4, 1960; and January 28, 1967 flares are given in Chapter IV. These spectra, relating to $R > 1$ Gv, are also satisfactorily described by the power function $\sim R^{-\gamma}$.

The fact, that exponential form of the spectrum is not always suitable, does not contradict the observational data used by Freier and Webber [6]. As a matter of fact, the above authors [6] obtained the information about the low-energy solar particles from the data of riometers whose sensitivity decreases rapidly at $\mathcal{E}_k \lesssim 15$ Mev.

The dependence of the magnitude of absorption of cosmic radio noise on the spectrum of solar particles is illustrated in Fig. 8.10 taken from the work [6]. Here the continuous curves show the absorption, calculated on the basis of riometric data at a frequency of 30 MHz and caused by solar protons of integral spectrum $I = I_0 e^{-R/R_0}$ at $I_0 = 10^3$ proton. cm^{-2}. sec^{-1}. sterad^{-1} and $R_0 = 50, 100, 200$ Mv. The value of absorption at an arbitrary value of I_0 can be obtained from these curves by multiplying the value of the amplitude obtained from the Fig., by $\sqrt{I_0/10^3}$. The dotted lines show the absorption due to protons of spectrum $dI/d\mathcal{E}_k = K \mathcal{E}_k^{-\gamma}$ at $\gamma = 4$. The value of K is selected in such a manner that integral intensity of particles at R = 450 Mv(100 Mev) is equal to 0.1 proton. cm^{-2}. sec^{-1}. sterad^{-1}.

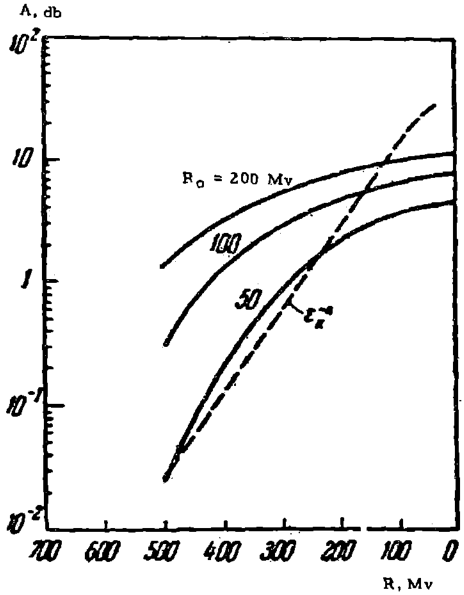


Fig. 8.10. Dependence of the absorption of cosmic radio noise on the rigidity of protons (continuous lines) at R_0 = 50, 100, 200 Mv and on their energy (dotted line) for the spectrum $\sim \mathcal{E}_k^{-4}$.

Based on the data given in Fig. 8.10, it is interesting to point out that on using the exponential spectrum, the effect of latitude on absorption is found to be weaker for riometers installed north of 69° geomagnetic latitude ($R \approx 100$ Mv). This is due to the fact that in the case of vertically falling particles, the maximum absorption per particle is observed to be in the range $\mathcal{E}_k = 20$-40 Mev. At still lower energies, the sensitivity of the riometer decreases because the particles get arrested high up in the atmosphere where the frequency of their collosions with air atoms is low. This decrease in sensitivity is possibly compensated by the increase in the steepness of the spectrum (at $R_0 \leq 50$ Mv) when at least half of the total absorption is caused by the particles with $\mathcal{E}_k < 20$ Mev.

It follows from the above that the extrapolation of the spectrum from the riometric data for $\mathcal{E}_k > 15$ Mev, to the region of extremely low rigidities (right up to $R = 0$) leads to an error in the calculation of I_0. The value of I_0, obtained by extrapolation, can be a suitable parameter for describing the spectrum in the region of high energies but it does not essentially correspond to the intensity of particles of rigidity close to zero. It should also be pointed out that the dependence of rigidity $R_0(t)$ on time and its change from flare to flare, still more complicate the interpretation of experimental data. Obviously, the exponential form of the spectrum for the solar particles cannot be taken as the universal spectrum.

Let us consider some more effects relating to the interpretation of the observed spectrum of solar particles.

The motion of magnetic irregularities in the interplanetary space does not have a noticeable effect on the spectrum of solar particles in the beginning of the flare and at the initial stage of the decrease in intensity at the Earth's orbit. However, this effect can be significant at later stages especially for particles giving rise to polar absorptions of short radio waves (see Section 14.9). Obviously, the drifting of particles in the irregular interplanetary fields cannot explain some of the peculiarities of cosmic-ray flares, e.g., the significant delay of low-energy particles as compared to high-energy particles. Antifermi retardation in the diverging beam of irregularities becomes noticeable only for particles of extremely low energy whose spectrum in this case, according to L. I. Dorman [I. 59] becomes more plane.

Thus, the interpretation of the spectrum of solar cosmic rays, measured at the Earth's orbit, is based on two fundamental assumptions: 1) the peculiarities of the spectrum near the Earth are defined by the characteristics of the mechanisms of acceleration and exit of particles from the origin on the Sun (local magnetic trap); 2) the shape of emission spectrum hardly changes from flare to flare and its peculiarities near the Earth are defined by the diffusion (exit) of particles out of the trap of the solar system. It is not eliminated that both these possibilities may occur simulataneously but the modern state of this problem does not facilitate estimation of their relative role in the formation of spectrum of solar cosmic rays.

9. COMPOSITION OF SOLAR COSMIC RAYS

Protons are the main constituents of solar cosmic rays. Investigations conducted during the earlier years led to the detection of various nuclei with $Z \geqslant 2$ as well as electrons and neutrons. The very fact of their presence, energy spectra and relative content are of great importance not only for studying solar cosmic rays but also for understanding the physics of the Sun and for studying the nonsolar cosmic rays.

The first significant successes in the study of composition of solar cosmic rays was achieved during the years of the last maximum solar activity (1957-62). At present, the picture is more or less clear in general, and therefore, main attention is being paid to the details of this problem.

We have, of course, the most elaborate information on protons.

The energy spectra of solar protons and helium nuclei were simultaneously measured in a number of cases with the help of photo emulsions on balloons (Biswas et al. [I. 81], Biswas and Freier [15], Ney and Stein [I. 82], Freier and Webber [6], Freier [10, 11]) and on rockets (Biswas et al. [28; I. 24]). In spite of their limited number, these measurements are of much significance since the difference in charge to mass ratios for protons and α-particles facilitates differentiation of their beams according to velocities and rigidities.

With regard to the isotopic composition, significant fluxes of deutron were recorded in two cases (Balasubrahmanyan et al. [29]) and sufficiently rigid upper limits were obtained in two other cases (Biswas et al. [I. 24], Waddington and Freier [I. 28]). The presence of tritium and He^3 in solar cosmic rays was also detected (Fireman et al. [30], Tilles et al. [31], Schaeffer and Zahringer [I. 56]).

Small fluxes of still heavier nuclei were also recorded in a number of experiments (Fichtel and Guss [32], Biswas et al. [28; I. 24], Yagoda et al. [33], Pomerantz and Witten [34], L. V. Kurnosova et al. [35], Biswas and Fichtel [36]). Apparently, these nuclei are always present in solar cosmic rays since they are recorded every time when the observed intensity of solar particles is sufficiently high so that one expects the appearance of heavy nuclei on the basis of their relative content in other cases.

The detailed investigation, conducted by Biswas et al. [I. 24] and Biswas and Fichtel [36], shows that the composition of nuclei with $Z > 2$ is apparently similar to the composition of solar atmosphere and considerably differs from the composition of cosmic rays beyond the limits of the solar system.

According to the observations of Earl [I. 122], Ney and Stein [I. 82] and Cline et al. [V. 130], the intensity of high-energy electrons in the interplanetary space is very low. As a matter of fact, the measurements of Meyer and Vogt [V. 125] are the only available convincing proof of the existence of electrons caused by solar flares. These scientists with the aid of balloons, observed a significant flux of electrons over Churchill on July 22, 1961. However, even in this case, their intensity was extremely small as compared to the intensity of protons (see Section 22).

There is no direct indication about the presence of solar neutrons in flares but a number of considerations point out the possibility of their generation on the Sun (see Section 23).

In this section, basic experimental results on charge and energy spectrum of solar nuclei are described and the data on isotopic composition of hydrogen and helieum nuclei are also given.

9.1 Distribution of solar nuclei according to charge and their spectra depending upon the energy and rigidity. At present, it is appropriate to mention only of multiple-charged nuclei ($Z \geqslant 2$) since obviously there is no specific relation between the fluxes of protons and heavier nuclei. This conclusion follows from the similarity in the composition of nuclei $Z \geqslant 2$ (independent of the energy), from the data on different flares and for different periods during a particular flare and from the fact that the relation between fluxes of protons and α-particles changes significantly from flare to flare.

The results obtained by different authors using different types of equipment installed on balloons, rockets and satellites are summarized in the detailed review of Biswas and Fichtel [37].

In the case of balloon measurements, the minimum energy of detected particles is determined by the atmospheric absorption (about 75 Mev/nucleon) or by the cut-off rigidity in the geomagnetic field. If the measurements are made near the magnetic poles with the aid of rockets or satellites, the lower limit of the energy of detected particles is defined by the parameters of the detector itself. This limit is usually of the order of $\varepsilon_k \lesssim 10$ Mev.

Since the solar particles are distributed not only according to the charge but also according to their velocities, it is necessary to study with the passage of time, the change in their nuclear composition as well as in the distribution of velocities. In addition, the possible variants of these distributions for different cases should also be taken into account. Finally, it is advisable in each case to differentiate the effects of velocity and rigidity of particles since the acceleration and distribution of solar cosmic rays may depend on both the parameters.

While analyzing the data, it should be kept in view that the ratio Z/A for protons is about twice the corresponding ratio for nuclei with $Z \gg 2$ from which at a given speed, we get $R_p \approx 1/2\, R_{Z \geq 2}$

In those cases, when the fluxes of protons and other nuclei are measured simultaneously, it is possible to write simple expressions describing the distribution of particles according to the rigidities or energies per nucleon in a limited range:

$$dI/d\varepsilon = C(A, Z, t)(\varepsilon/\varepsilon_0)^{-\gamma(A, Z, t)}, \tag{9.1}$$

$$dI/dR = K(A, Z, t)\exp[-R/R_0(A, Z, t)], \tag{9.2}$$

where I is the integral intensity of particles; A is the atomic number of the element; Z is the charge of the nucleus; ε is the total energy; ε_0 is the potential energy and R_0 is the characteristic rigidity.

Although these expressions explain the spectrum of solar particles in a simple manner in a limited range of energy or rigidity, it should be kept in view that neither (9.1) nor (9.2) is applicable for all energies and for all instants of time (see Section 8). The measured values of γ and R_0 are given in Table 9.1. The ratios of the flux of protons to that of helium and of protons to medium nuclei are shown in Table 9.2. Both the tables show the results of only those experiments in which measurements were taken on more than one component of solar cosmic rays.

As shown by Freier and Webber [6] for the first time, the rigidity spectra of protons and helium nuclei are often similar in shape, i.e., the parameter R_0 in formula (9.2) is approximately the same for these two types of particles. The differential rigidity spectra of protons, α-particles and medium nuclei, recorded by Biswas et al. [I.24] on November 16, 1960 at 1951 UT, are shown in Fig. 9.1 as an example but the flux of medium nuclei was multiplied by 60 to superpose the spectra.

However, the observation of Freier and Webber [6] are not always complied with. The values of R_0 differed significantly at 1603 UT on November 13, 1960, at 1405 UT and at 0930-1700 UT on September 3, 1960 when it was possible to measure the spectra of protons and multiple-charged particles

TABLE 9.1

Values of γ and R_0 in the spectra of solar protons, α-particles and medium nuclei

Time of measurement, UT	γ			R_0		Source
	Protons	α-particles	Medium nuclei $6 \leq Z \leq 9$	Protons	α-particles and medium nuclei	
14.08 September 3, 1960	-11.9±0.4	-27.0±2.1	-	169.6±6.9	132.6±7.2 *)	[1.81], [32, 36]
18.40 November 12	-20.7±2.4	-56.3±7.2	61.8±9.6	119.3±7.0	103±9.9	[21, 36]
16.03 November 13, 1960	-37.4±2.2	-59.7±8.2	-64.4±8.9	78.0±3.9	109.2±6.7	[21, 36]
10.30-12.30 November 15, 1960	-	-	-	175	175 *)	[1.82]
14.30-17.30 November 16, 1960	-	-	-	100	100 *)	[1.82]
19.51 November 16, 1960	-26.5±3.4	-70.8±10.8	-63.8±8.4	103.3±10.0	107.2±10.4	[36; 1.24]
06.00 November 17, 1960	-32.4±2.1	-63.8±9.9	-71.0±11.0	89.7±5.7	102.9±12.4	[36; 1.24]
03.39 September 18, 1960	-36.7±2.6	-60.8±8.4	-60.7±12.3	81.3±6.4	113.9±95.5	[36; 1.24]
15.35-17.50 July 18, 1961	-	-	-	160	160 *)	[6]
21.10-23.30 July 18, 1960	-	-	-	125	125 *)	[6]

*) Only for α-particles.

TABLE 9.2

Ratio of the flux of protons to that of helium A(p, He, $\mathcal{E}$) and of medium nuclei A(p, M, $\mathcal{E}$)*

Time of solar flare, UT	Time of measurement, UT	Measuring method	Energy interval, Mev/nucleon	A(p, He, $\mathcal{E}$)	A(p, M, $\mathcal{E}$)	Rigidity interval R, Gv	A(p, He, R)	A(p, M, R)	Source
1	2	3	4	5	6	7	8	9	10
02.10 July 10, 1959	07.55-16.25 July 11, 1959	Balloons	≥ 80	59±6	-	≥ 0.79	1.4 ± 0.2	-	[6] [11]
	12.25-23.45 July 12, 1959	Balloons	≥ 80	430±70	-	≥ 0.79	5.0±0.8	-	[6] [11]
10.15 May 4, 1960	17.00-02.00 May 4-5, 1960	Balloons	-	-	-	0.7-1.6	≥50	-	[6], [15]
00.37 September 3, 1960	09.30-17.00 September 3, 1960	Balloons	-	-		0.4-0.6	31	-	[1.81]
	16.50-23.20 September 4, 1960	Balloons	115-180	185	-	0.4-0.6	19	-	[1.81]
	14.08 September 3, 1960	Rockets	42.5-95	43±14	2650±790	0.57-0.87	20±7	1100 ± 380	[32; 1.24]
13.22 November 12, 1960	18.40 November 12, 1960	Rockets	42.5-95	32±6	2000±400	0.57±0.87	5±1	300±55	[28]
	04.00 November 13, 1960	Satellites	-	-	-	1.5-2.0	-	260 **	[34]
	05.43 November 13, 1960	Satellites	-	-	-	2-2.5	-	260 **	[34]
	16.03 November 13, 1960	Rockets	42.5-95	36±7	2650±430	0.57-087	1±0.2	68±14	[28]
	23.06 November 13, 1960	Satellites	-	-	-	1.1-1.9	-	∼ 260	[34]
	00.24 November 15, 1960	Satellites	-	-	-	1.0-1.2	-	260 **	[34]
02.07 November 15, 1960	10.30-12.30 November 15, 1960	Balloons	-	-	-	0.81-1.08	-	100 ***	[1.82]
	14.30-17.30 November 15, 1960	Balloons	-	-	-	> 0.8	1.6	-	[1.82]
	19.51 November 16, 1960	Rockets	42.5-95	23±5	1410±200	0.57-0.87	1.7±0.5	100±23	[1.24]
	19.51 November 16, 1960 19.51	Rockets	3-17.5	9.5+2.5	-	0.15-0.36	1.6±0.6	-	[38]

	November 16, 1960	Rockets	0.55-2.5	-	-	0.064-0.137	3.7±0.9	-	[38]
	23 38 November 16, 1960	Satellites	-	-	-	0.85-1.5	-	260 **	[34]
	06.00 November 17, 1960	Rockets	42.5-95	59+13	2230±370	0.57-0.87	2.5±0.6	95±19	[1 24]
	23.14 November 17, 1960	Satellites	-	-	-	0.6-1 0	-	~1000**)	[34]
	03.39 November 18, 1960	Rockets	42.5-95	51±11	2720±560	0.57±0.87	1.7±0.5	92±24	[1.24]
09.20 July 18, 1961	15.35-17.50 July 18, 1961	Balloons	-	-	-	0.8-1 3	6±1	-	[6, 10]
	13.05-19.18 July 18, 1961	Balloons	115-195	-	(1.9±0.6)x10^4	0.95-1.27	-	212±68	[39]
	21.10-23 30 July 18, 1961	Balloons	-	-	-	0.8-1.3	6±1	-	[6, 10]
15.55 March 16, 1964	Most of the duration of the event	Satellites	15-75	> 200	-	-	-	-	[29]
17 50 February 5, 1965	Most of the duration of the event	Satellites	15-75	> 200	-	-	-	-	[29]

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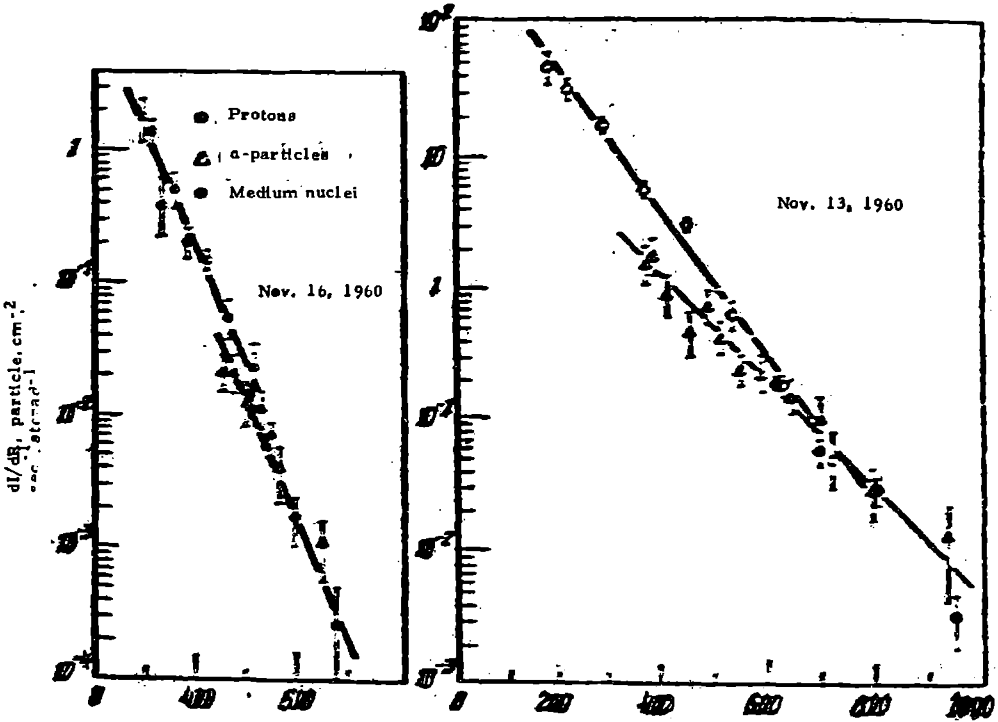
* A(i, j, k) is the ratio of flux of particles of type i in the interval k to that of particles of the type j in the same interval.

** Ratio A(p, M+H, R).

*** Rigidity range for medium nuclei is 1 18-1.45 Gv.



a) b)

Fig. 9.1. Differential rigidity spectra of protons, α- particles and medium nuclei.

a) at 1951 UT on November 16, 1960; b) at 1603 UT on November 13, 1960.

To superpose the spectra, the flux of medium nuclei was multiplied by 60.

in a wide range of rigidity. An analysis of these data, by Biswas and Fichtel [36], showed that the probability of agreement of the values of R_0 for protons and α-particles in the above-mentioned cases was less than 0.1%.

Fig. 9.1,b shows the rigidity spectra of solar protons, α-particles and medium nuclei recorded at 1603 UT on November 13, 1960 (as in Fig. 9.1, a, the flux of medium nuclei is multiplied by 60). Observations were made with the aid of photoemulsions mounted on balloons and rockets (see the references in Table 9.2). In the balloon experiments, the measurements covered the energy range of 300-800 Mev for protons and 80-300 Mev/nucleon for α-particles whereas in subsequent measurements, for proton and α-particles, the range studied was 15-300 Mev and 30-130 Mev/nucleon respectively.

It was established, that, in spite of the similarity in rigidity spectra, the ratio of the flux of protons to that of α-particles in the given rigidity range changes significantly from event to event and from time to time during the course of the given event. At $R > 0.8$ Gv, this ratio changes within the limits 1-50 and a tendency to stick to lower values is observed. Some of the ratios obtained experimentally are given in Table 9.2. The data are taken from the work of Freier and Webber [61 for $R \gtrsim 0.8$ Gv and of Biswas and Fichtel [36] for $R = 0.5$-1.0 Gv. Moreover, Table 9.2 also contains the data of Balasubrahmanyan et al. [29] obtained with the aid of counting telescope on board the satellites of the type "IMP"

In all those cases where the fluxes of protons and α-particles were measured in the same range of energy per nucleon, the energy spectrum of α-particles was much more steeper than that of protons. Fig. 9.2 shows a typical example of such an effect at 1951 UT on November 16, 1960 based on the data of Biswas et al., [I.24] (flux of α-particles is multiplied by 10 and that of medium nuclei by 600). The corresponding values of γ, obtained on the basis of relation (9.1), are given in Table 9.1.

While studying the relation of protons to α-particles at a given velocity range, it is necessary to precisely define this range since the relation, as is obvious from Fig. 9.3, may depend significantly on the energy. In addition to these changes during a particular event, it is pointed out that the ratio of protons to α-particles in a given velocity range may change significantly from event to event. Table 9.2 gives the ratios measured for those cases for which it was possible to compare the fluxes of protons and α-particles in the same range of energy per nucleon. Data on protons, used for comparing with the flux of α-particles in [39], were obtained by Guss and Waddington [40] by measuring with an emulsion pile similar to the one used in the work [39].

9.2. Multiple-charged nuclei. Information about heavy nuclei ($Z \gtrsim 3$) is, at present, more limited than the data on protons and α-particles. Since the mean free path without interaction in air is small for heavy nuclei, almost the whole of the information about these particles was obtained with the aid of

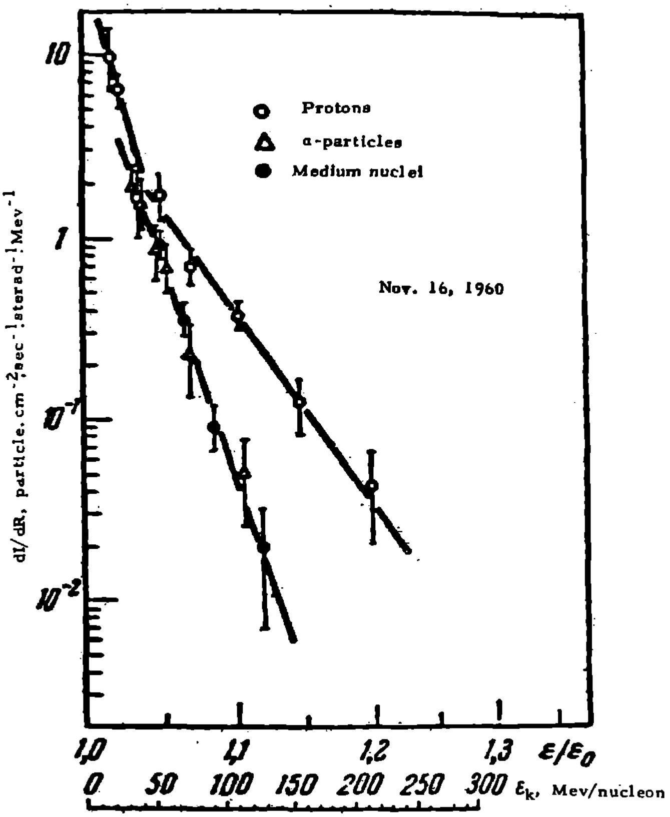


Fig. 9.2. Differential energy spectra of protons, α-particles and medium nuclei at 1951 UT on November 16, 1960 [I.24]. To properly superpose the spectra, the flux of He-nuclei is multiplied by 10 and that of medium nuclei by 600.

rockets and satellites. Only in two cases the high-energy heavy nuclei of solar origin were recorded by balloons.

Heavy nuclei were detected for the first time by Fichtel and Guss [32] during the September 3, 1960 flare event with the help of nuclear photoemulsions mounted on a rocket over Churchill. Later on, these nuclei were recorded during November 1960 by Biswas [28], Yagoda et al. [33], and Ney and Sten [I.82] using photoemulsions on balloons, rockets and sattellites, and by Biswas and Fichtel [36] using a system of Cerenkov detectors. The increase in the flux of heavy nuclei on July 18, 1961 was confirmed by balloon-borne emulsion measurements taken by Biswas et al. [39].

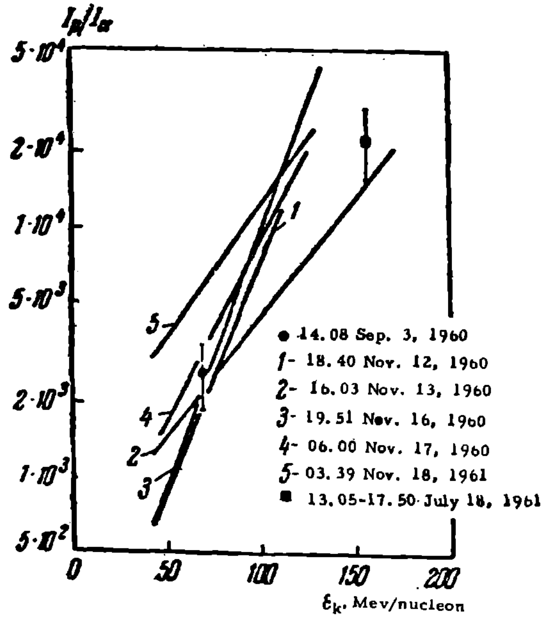


Fig. 9. 3. Ratio of the intensities of protons and α-particles as a function of kinetic energy per nucleon.

The presently available data confirms that the spectra of α-particle and medium nuclei, according to the energies per nucleon, have the same shape. The values of γ in equation (9.1), calculated by Biswas and Fichtel [36] for α-particles and medium nuclei, agree within the limits of experimental error (see Table 9.1). Moreover, since the medium nuclei have the same Z/A ratio as helium, their rigidity spectra must have the same shape, of course, if one assumes that the nuclei have completely lost their electron shells. Similarity in spectra of helium and medium nuclei becomes obvious from Figs. 9.1 and 9.2.

During the above-mentioned three flares, it was possible to measure the relative content of helium and medium nuclei in the same rigidity range and it was found that the relative content was the same within the limits of experimental errors (see Table 9.3). A change in this ratio, within the limits of two standard errors, is obviously not very important since one such deviation at 0600 UT on November 17, 1960 is quite possible statistically, whereas the deviation in the other two cases of the same flare does not go beyond one standard error. It follows from this that, since the ratio of helium to medium nuclei remains constant, the ratio of protons to medium nuclei should change exactly in the same manner as the ratio of protons to helium (see Fig. 9.3).

TABLE 9.3

Ratio of the flux of α-particles to that of medium nuclei

Time of measurement, UT	Energy range $\Delta\mathcal{E}$ Mev/nucleon	$A(\mathrm{He}, M, \Delta\mathcal{E})^*$	References
14.08 September 3, 1960	42.5 - 95	68 ± 21	[32; 1.24]
18.40 November 12, 1960	42.5 - 95	63 ± 14	[21]
16.03 November 13, 1960	42.5 - 95	72 ± 16	[21]
19.51 November 16, 1960	42.5 - 95	61 ± 13	[1.24]
06.00 November 17, 1960	42.5 - 95	38 ± 10	[1.24]
0.3.39 November 18, 1960	42.5 - 95	53 ± 14	[1.24]
Average of 6 events	42.5 - 95	60 ± 7	
12.25-23.45 July 12, 1959	150 - 200	$\geqslant 100 \pm 35$	[28]
10.30-12.30 September 15, 1960	175 - 280	$\approx 100^{+100}_{-50}$	[1.82]
13.05-19.18 July 18, 1961	120 - 204	69 ± 16	[39]

* A(i, j, k) is the ratio of the flux of particles of the type i in the range k to the flux of particles of the type j in the same range.

According to the data obtained by five independent measurements by Biswas et al. [I.24; 21], the relative content of heavier nuclei in the flux of all the nuclei, measured in a constant range of energy per nuclean, during two flares (Table 9.4), was found to be the same. This result facilitates the assumption that at a sufficient flux of heavier nuclei in a wide rigidity range, their rigidity spectrum will be the same as that of α-particles and medium nuclei.

TABLE 9.4

Relative content of heavier nuclei at constant energy per nucleon (oxygen content is taken to be equal to 10) [I. 24; 21]

Time of measurement, UT	Charge of the nucleus						
	4+5	6	7	8	9	10	11
18.40 November 12, 1960	<0.2	4.8 ± 1.0	1.7 ± 0.7	10	<0.3	1.4 ± 0.5	1.1 ± 0.2
16.03 November 13, 1960	<0.2	7.1 ± 1.5	1.9 ± 0.8	10	<0.3	1.2 ± 0.5	1.6 ± 0.2
19.51 November 16, 1960	<0.3	6.5 ± 1.3	2.9 ± 0.9	10	<0.5	2.0 ± 0.8	1.2 ± 0.2
06.00 November 17, 1960	<0.3	6.0 ± 1.8	2.1 ± 1.0	10	<0.6	2.0 ± 1.1	1.7 ± 1.2
03.39 November 18, 1960	<0.5	4.9 ± 1.9	1.0 ± 0.7	10	<1	0.7 ± 0.7	1.0 ± 1.0
Average or limiting value	<0.2	5.9 ± 0.7	1.9 ± 0.4	10	<0.3	1.5 ± 0.3	1.3 ± 0.4

TABLE 9.5

Relative content of nuclei (amount of oxygen nuclei is taken to be equal to 1.0)

Elements	Solar cosmic rays [I.23; 21)	Sun* [46, 47]	Universe* [48, 49]	Galactic cosmic rays** [50]
$_2$He	107 ± 14	?	150	48
$_3$Li	-	$< 10^{-5}$	$< 10^{-5}$	0.3
$_4$Be-$_5$Be	< 0.02	$< 10^{-5}$	$< 10^{-5}$	0.8
$_6$C	0.59 ± 0.07	0.6	0.26	1.8
$_7$N	0.19 ± 0.04	0.1	0.20	≲ 0.8
$_8$O	1.0	1.0	1.0	1.0
$_9$F	< 0.03	0.001	$< 10^{-4}$	≲ 0.1
$_{10}$Ne	0.13 ± 0.02	?	0.36	0.30
$_{11}$Na	-	0.002	0.002	0.19
$_{12}$Mg	0.043 ± 0.011	0.027	0.040	0.32
$_{13}$Al	-	0.002	0.004	0.06
$_{14}$Si	0.033 ± 0.011	0.035	0.045	0.12
$_{15}$P-$_{21}$Sl	0.057 ± 0.017	0.032	0.024	0.13
$_{22}$Ti-$_{28}$Ni	≲ 0.02	0.006	0.033	0.28

* Uncertainty of the value in these columns of the Table is probably of the order of a factor of 0.5.
** Uncertainty of the value in this column varies from 10 to 30%.

Thus, on the basis of the data obtained, it is possible to study the relative abundance of multiple-charged nuclei in the composition of solar cosmic rays but a better estimate of the relative content can be obtained by using the average data of all the recorded events in a constant velocity range. Data on five flights, averaged in this way, are given in Table 9.5 by taking oxygen content to be equal to unity. It is obvious from Table 9.5 that medium nuclei ($6 \leq Z \leq 9$) constitute most of the heavy nuclei ($Z > 2$) whereas the Be and B nuclei were so few that it was possible to determine only the upper limit of their content.

The detailed analysis shows that the relative abundance of energetic solar particles within the limits of the errors agrees with the composition of solar atmosphere determined spectroscopically. Since the abundance of elements on the Sun is similar (but not identical) to their abundance in the Universe, solar cosmic rays also have such a similarity. On the other hand, the composition of solar cosmic rays considerably differs from that of galactic cosmic rays which, as is well-known, are richer in heavy nuclei.

In some measurements, undertaken by a group of Soviet research workers under the guidance of L. V. Kurnosova [35], increases of duration of 2 to 20 minutes in the flux of heavy relativistic nuclei ($\gtrsim 600$ Mev/nucleon) were recorded and which were not connected with the usual flares of solar cosmic rays. A part of these measurements was obtained on a satellite-borne system of Cerenkov counters. Although, in other experiments as well, there was a possibility of recording similar effects [41], no such increases were observed in the measurements [41]. This aspect is considered in more detail in Section 9.4

Regarding the discovery of heavy nuclei ($Z > 2$) in solar cosmic rays, many interesting questions arise, and a final answer will be only possible after conducting additional experiments.

In this connection, the results of Biswas et al. [39] on the measurements of helium and heavy nuclei during the July 18, 1961 flare event are of great interest. These results support many assumptions put forward earlier regarding the measurement of solar particles in the three previous powerful flares during which heavy nuclei were recorded: September 3, 1960 (Fichtel and Guss [32]); November 12, 1960 (Biswas et al. [21], Yagoda et al. [33], Pomerantz and Witten [34]); November 15, 1960 (Ney and Stein [I.82], Biswas et al. [I.24], Biswas and Fichtel [37]).

Emulsion measurements [39] were made with the help of balloons launched over Chruchill and which drifted to a medium altitude with the residual pressure of 2.07 g/cm^2. The emulsion pile was rotated vertically when the balloon attained the "ceiling" and remained in this position during 1305 UT and 1918 UT on July 18, 1961. According to the riometer data 30 MHz at Churchill, polar absorption started at about 1100 UT on 18th July, attained a maximum value of about 8 db at 1200 UT and remained at this level for the rest of the day. The latter fact signifies that the average flux of particles during the exposure of the pile did not change significantly. The tracks were processed in such a manner that the minimum energy of medium nuclei ($6 \lesssim Z \lesssim 9$) was about 120 Mev/nucleon and the maximum, 204 Mev/nucleon. In all, 51 tracks for heavier nuclei and 73 tracks for helium were analyzed.

Extrapolation of the intensity of helium nuclei to the atmospheric boundary is, to some extent, indefinite because of the absence of information about the energy dependence of the mean free path of these nuclei in air and in emulsion. In the given case, this parameter plays a leading role as the contribution of helium nuclei, due to secondary particles and due to fragmentation of heavy nuclei, to the observed flux is very small in the considered energy range. At large energies, the mean free path for absorption is equal to 21.4 cm in emulsion (51 g/cm^2 in air); at extremely low energies, the corresponding values are very high. It was found that by considering the absorption and by neglecting the corrections -0.86 x 10^3, the intensity of helium nuclei at the atmospheric boundary was equal to $\sim 1.03 \times 10^3$ cm^{-2}, sec^{-1}, sterad^{-1}. A compromise value of $0.95 \pm 0.13 \times 10^3$ was selected for analysis. The intensity of medium nuclei was found to be equal to 12.0 ± 1.8 cm^{-2} sec^{-1}, sterad^{-1} in the range ε_k = 120-204 Mev/nucleon. Thus, the ratio of the flux of helium nuclei to that of medium nuclei was equal to 79 ± 16.

Fig. 9.4 shows the energy spectra of these two groups of nuclei. It is obvious that if the flux of medium nuclei is multiplied by 60, i.e., by the average ratio of the fluxes of helium and medium nuclei, obtained by Biswas and Fichtel [39] for the previous cases, the spectra are the same and within the limits of a narrow interval of change. If the results of this work are compared with the results of six other experiments mentioned in Table 9.3, and by assuming that all the experiments are similar in nature, we obtain the ratio of helium nuclei to medium nuclei equal to 62±6.

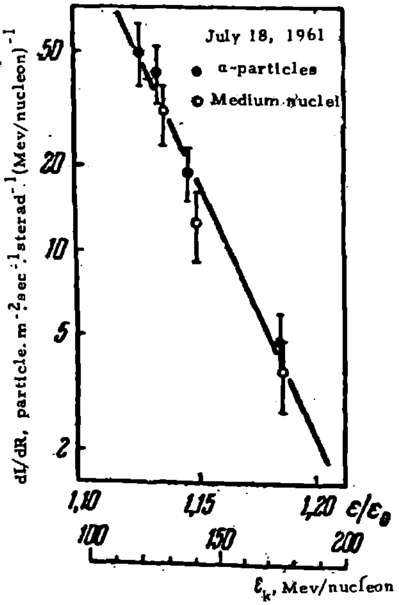


Fig. 9.4. Differential energy spectra of particles and medium nuclei on July 18, 1961 [39].

Out of 9 heavy nuclei, which do not fall under the group of medium nuclei, only one nucleus was found to be light one ($3 \leqslant Z \leqslant 5$). Due to the presence of matter over the detector in which light nuclei might be formed and due to limited possibilities for determining the charge, it is possible to mention only the upper limits of the flux of light nuclei and it was found to be equal to 0.7 of the flux of medium nuclei. The remaining 8 nuclei had a charge from 10 to 14 and had the same range of mean free path. It follows from this that they had higher energy per nucleon. Based on the obtained flux of medium nuclei and their relative content in the previous cases, the presence of 5 nuclei with charge between 10 and 14 should be expected so that the measured amount may be in conformity with their content as in the previous cases.

The flux of helium nuclei in the composition of galactic cosmic rays during this period of solar cycle has been obtained by Fichtel et al. [42] whereas the flux of heavier nuclei can be estimated from the data on composition of cosmic rays, taking in account the results of measurements obtained for low-energy nuclei during the previous year (Fichtel et al. [43], Balasubramanyan et al. [29], Comstock et al. [44], Reames et al. [45]). The values obtained for the intensities in the units of particles$\cdot$ cm^{-2} sec^{-1} $sterad^{-1}$ are 6.9 ± 11 for helium in the range 120-204 Mev/nucleon, 0.23 ± 0.05 for medium nuclei and 0.07 ± 0.02 for nuclei having $Z \geqslant 10$ in the same energy range. Thus, the contribution of galactic particles to the flux of solar nuclei can be neglected.

The observation of heavy nuclei on July 18, 1961 includes this case in the group of four previous flares during which heavy nuclei were detected.

According to Biswas and Fichtel [37], the composition of solar nuclei, in detail, reflects the composition of the solar atmosphere only within those limits where a comparison is possible. The carbon to oxygen ratio measured by Biswas et al. [39], agrees with the value of 0.6 obtained earlier. The small amount of light nuclei is also in conformity with the previous estimates. The amount of heavy nuclei ($Z \geqslant 10$) also does not contradict other experiments.

These results, especially the marked constancy of the ratio of helium to medium nuclei, support the assumption that the composition of multiple-charged nuclei is apparently retained from flare to flare. In Table 9.5, the results of measuring the composition are summed up and a comparison is made with the abundance of nuclei on the Sun, in the Galaxy and in the galactic cosmic rays. As already mentioned, the composition of solar cosmic rays is similar to that of the solar atmosphere and significantly differs from the composition of galactic cosmic rays. Since the significance of this fact was discussed in detail earlier [37], only a few additional comments will be made here.

1) Since the Sun is characterized by the presence of elements typical of the most ordinary star and since this content is obviously reflected in the composition of solar cosmic rays, it is proper to conclude that the difference in the nuclear composition of galactic cosmic rays and ordinary stars is the only source of galactic cosmic rays. Therefore, galactic cosmic rays have probably an extremely specific source, possibly Supernova stars (see, for example, [I.21]).

2) Energetic nuclei coming from the Sun with charges from $Z \geqslant 2$ to a maximum of $Z = 20$ obviously reflect the composition of the solar atmosphere. If the composition of these nuclei is taken to be characteristic of the Sun, their relative abundance, given in Table 9.5, can be used for estimating the abundance of helium and neon on the Sun by considering that it is not possible to correctly estimate their content in the photosphere by spectroscopy. The average ratio of helium to oxygen is equal to 107 ± 14 while that of neon to oxygen is 0.13 ± 0.02 (Biswas and Fichtel [37]). According to the estimates of Suess and Urey [48] and Cameron [49], the ratio of neon to oxygen is close to their abundance in the Universe although it is slightly less than that in the Universe. The ratio of helium to medium nuclei is typical; however, the ratio of protons to helium is of great importance. Due to several factor which are related to the different energy spectra and to the charge to mass ratio, there are no simple, real methods of determining this ratio only from the data on solar cosmic rays. If the ratio of helium to medium nuclei, equal to 62 ± 7, is considered to be characteristic for the Sun and the ratio of protons to medium nuclei, obtained by spectroscopy, viz. 650 (Aller [46], Goldberg et al. [47]), is used, we get the ratio of protons to helium to be of the order of 10.5 ± 4.0. The accuracy in this value depends on the accuracy of assumptions made above and on the correctness in the ratios of protons and helium to medium nuclei. Thus, the estimated error in the ratio of protons to helium is large and incorrect.

3) Hoyle and Taylor [51] pointed out that the low order of the ratio of hydrogen to helium obtained by the above-mentioned

method along with other similar ratios observed for other cosmic objects does not agree with the ratios expected from the assumption that the relative abundance of hydrogen and helium in the Universe is mainly determined by the processes going on in the ordinary stars. Hoyle [52] considers that this result facilitates the assumption that the density of matter in the Universe was more in the past than at present.

4) Since the mechanism of propagation has a similar effect on particles with the same charge to mass ratio, the similarity in the energy spectra of helium and medium nuclei and the constancy in the composition of multiple-charged nuclei are probably the properties of particles at the end of the acceleration phase. In order to explain these effects, it is convenient to consider Fermi's acceleration mechanism [I. 57; 53]. Hayakawa et al. [54] concluded that the Fermi process is the dominating process during the acceleration of nuclear particles in the non-relativisitic region. It was shown earlier (Biswas et al. [21]) that, in general, the spectrum, simultaneously depending on the velocity and rigidity of particles, can be obtained as a result of Fermi process and that the particles having low charge to mass ratio will have a steeper energy spectrum in the region of high energies. This modified Fermi mechanism must lead to similar spectra for all nuclei having the same charge to mass ratio; however, the spectra for protons and α-particles will be different, and this is observed in actual practice.

Similarity of charge spectra of multiple-charged nuclei in solar cosmic rays is an interesting feature and this is due to important physical changes occurring as a result of significant changes in many other characteristics of solar particles.

Till this time, there is no proof of the fact that the relative abundance of multiple-charged nuclei in solar cosmic rays, in every case, reflects the composition of the solar photosphere. If future experiments confirm it, a reliable estimate of the abundance of helium and neon will be obtained. Moreover, theories of acceleration of solar particles must be in conformity with the composition of multiple-charged particles reflecting the composition of the solar atmosphere while theories on the evolution of the Universe must conform to the observed hydrogen to helium ratio.

9.3 Isotopic composition of solar nuclei. By this time, some amount of data has been obtained on the isotopic composition of only hydrogen and helium nuclei*.

As mentioned earlier, protons constitute the largest part of single-charged solar nuclei. A number of experiments were conducted in earlier years to detect the possible existence of deuterons and tritons.

Based on the data of rocket measurements obtained during September 12, 1960 flare event, Biswas et al. [21] showed that the fraction of deuterons with respect to protons is less than 3×10^{-3} in the range ε_k = 25-48 Mev/nucleon. Later, on the basis of data of July 18, 1961 flare event, Waddington and Freier [I. 28] found an upper limit of this ratio to be equal to 2×10^{-3} in the range $\varepsilon_k > 50$ Mev/nucleon. Both these experiments were conducted with the aid of photoemulsions. According to the observation of Balasubramanyam et al. [29], the ratio of deuterons to protons was equal to 5×10^{-3} for protons with ε_k = 5-75 Mev and deuterons with ε_k = 20-100 Mev. This ratio was observed during the two events viz., February 5, 1964 and March 16, 1964. Since the particle spectrum rapidly decreases with energy, this ratio in the same interval of energy per nucleon will be slightly less than 5×10^{-3} but it will still have some finite value. Measurements [29] were made with the aid of a telescope of scientillation counters abroad the satellite "IMP-1" It is important to mention that extremely low solar activity, approximately equal to zero, coincided with the last two events when deuterons were actually recorded while the other two events were caused by powerful solar flares.

The finding of another isotope of hydrogen, namely, tritium, in the composition of solar cosmic rays is of great interest. Small amount of tritium was detected by the radiochemical method in the casing of the satellite "Discoverer-17" which was brought back to the Earth, and from an analysis of the data of rocket measurements on September 12, 1960 (Fireman et al. [30] Tilles et al. [31]). The observed flux of particles consisted of tritons temporarily trapped in the radiation belts and found in the satellite material, and of tritons apparently existing in galactic cosmic rays. It is difficult to make a quantitative estimate of the abundance of tritons due to the lack of direct observations of the integral flux of protons during the flight of the satellite "Discoverer-17".

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* *Recently B.M. Kuzhevskii [166] studied the possibility of generation of radioactive isotopes of heavy nuclei, especially of* Be^7 *and* Co^{56} *(see the remark on page 29).*

Considering most of the tritons to be of solar origin (Tilles et al. [31]) and taking the integral flux of protons with $\mathcal{E}_k > 30$ Mev within the limits from 10^9 cm^2.sec^{-1} (according to the estimate based on riometer data by Biswas and Fichtel [37] and on data of direct measurements made several times during November 12, 1960 flare) to 4×10^9 cm^{-2}. sec^{-1} (according to the estimate made by Lal et al. [I. 29] by the radiochemical method), we find the triton to proton ratio to be equal to $(1-4) \times 10^{-3}$ at $\mathcal{E}_k > 30$ Mev/nucleon. On the basis of the radiochemical analysis, Lal et al. [I. 29] arrived at the conclusion that more than 80% of the recorded tritons were secondary and hence, the ratio of tritons to protons in the region $\mathcal{E}_k > 30$ Mev/nucleon should apparently be reduced to 2×10^{-4}.

Based on rocket measurements obtained during the November 12, 1960 flare event, Tilles et al. [31] found the integral flux of tritons to be of the order of 8×10^4 cm^{-2}.sec^{-1} in the energy range of 0-27 Mev/nucleon. For the same flare, according to the data of rocket measurements made by Ogilwie et al. [55] with the help of scintillation counters, the integral flux of protons was found to be 8×10^7 cm^{-2}. sec^{-1} in the energy range of 2-27 Mev/nucleon. It follows from this that the ratio $H^3/H^1 \leq 10^{-3}$ for particles with $\mathcal{E}_k = 0-27$ Mev/nucleon. It was established by direct measurements, taken by Biswas et al. [21] with the aid of photoemulsions in the same rocket on November 1960, that the upper limit for the flux of tritons is equal to 0.7 cm^{-2}. sec^{-1}. sterad^{-1} in the range $\mathcal{E}_k = 20-45$ Mev/nucleon. The intensity of protons measured in the same experiment and for the same energy range was equal to 0.9×10 cm^{-2}. sec^{-1}. sterad^{-1}. Thus, the ratio of tritons to protons in the range 20-45 Mev/nucleon is either less than or equal to 10^{-3}. During July 18, 1961 flare event, Waddington and Freier [I. 28], while making emulsion measurements on balloons, established the upper limit of this ratio to be 0.6×10^{-3} in the region $\mathcal{E}_k > 50$ Mev/nucleon.

Thus, all the available experimental data show that the ratio of deuterons to protons in solar cosmic rays in the range $\mathcal{E}_k = 10\text{-}10^2$ Mev/nucleon is a value that is a few times multiplied by 10^{-3} or less while the ratio of tritons to protons is probably less than 10^{-3}. These ratios can apparently change from event to event and therefore, it is not surprising that the limit obtained for one event may be more rigid than that obtained for another event. Moreover, these ratios should obviously change depending upon the velocity range.

Waddington and Freier [I. 28] described an experiment to measure the relative abundance of hydrogen isotopes in high-energy particles generated during July 18, 1961 solar flare. Since the theory and method adopted to study the isotopic composition of solar cosmic rays, is of great interest, we will consider this work in more detail. The results of study of the isotopic composition, obtained by other authors, will also be discussed simultaneously.

It was shown by observations of Biswas et al. [I. 24] and Biswas and Fichtel [36] that the content of deuterons and tritons in the range $\mathcal{E}_k = 20\text{-}200$ Mev in solar cosmic rays is very low. From the above, it was immediately expected that the ratio of number of deuterons to that of protons having a velocity greater than $\Gamma_{dp}(>v)$ (or correspondingly, the energy per nucleon greater than the given $\Gamma_{dp}(>\mathcal{E})$ will be certainly less than 5×10^{-2} whereas the similar ratio for tritons should be still less. Therefore, in order to measure $\Gamma_{dp}(>\varepsilon)$ or $\Gamma_{tp}(>\varepsilon)$, it is very much necessary either to study the traces of a large number of particles at high permissible masses or to expose the detectors under such conditions when these ratios are large. If this increase cannot be measured in practice, then it means that the measurement of these small ratios is beyond the limits of the resolving power of the existing counting detectors and they can only be measured with the help of nuclear photoemulsions with extremely complex experimental techniques. However, if the detectors are exposed in the presence of a geomagnetic field, then there may be circumstances under which there is a possibility of a considerable increase in the value of these ratios.

Since deuterons and tritons have a charge-to-mass ratio different from that of protons, they are subjected to geomagnetic cut-off action differently and can penetrate to a given geographical point at a velocity less than that of protons. Consequently, the corresponding selection of geomagnetic threshold should, in principle, make it possible to observe a pure beam of deuterons and tritons without any proton contamination within a specified velocity range.

As a matter of fact, the geomagnetic thresholds determined experimentally are not very accurate. Even then, according to Earl [12], they have a tendency to decrease according to an exponential law and as such the differential intensity dI at some magnetic rigidity R, which is less than the rated cut-off rigidity (threshold) R_c, is determined from the formula

$$dI = dI_0 \exp\left[-\beta (R_c - R)\right], \tag{9.3}$$

where dI_0 is the differential intensity in the absence of geomagnetic field. In order to calculate these ratios, it is necessary to study the distribution of solar cosmic rays according to their velocities.

It was shown by Freier and Webber [6] that, in general, this distribution is best observed with the help of rigidity spectra in the exponential form $I = I_0 \exp(-R/R_0)$ where R_0 and I_0 are constants. Further, I_0 is a function of mass number A while R_0, generally speaking, does not depend on A at least for protons, α-particles and heavier nuclei. Consequently, the value of R_0 can approximately considered to be the same for deuterons, tritons and protons. This is the basic assumption in subsequent analysis and R_0 is considered to be independent of mass number. The value of R_0 was experimentally measured at least for two components during about 20 different events (Biswas and Fichtel [36], Freier and Webber [6], Freier [10]). Only during two events, Biswas and Fichtel [36] detected a significant change in the values of R_0 for different components.

Based on the above-mentioned assumption, the differential intensity of protons at a given rigidity can be represented in the form

$$(dI/dR)_p = -\Phi\,(I_{0p}/R_0)\exp\left(-R/R_0\right), \qquad (9.4)$$

where I_{op} is the corresponding value of I_0 for protons and Φ is the attenuation coefficient of intensity caused by the geomagnetic field; in accordance with equation (9.3) $\Phi = 1$ at $R > R_c$ and is determined by the exponential $\exp[-\beta(R_c - R)]$ at $R < R_c$. Similar expressions can be written for deuterons $(dI/dR)_d$ and tritons $(dI/dR)_t$ by replacing I_{op} by I_{od} and I_{ot} respectively.

Measurement at high altitudes show that different particles have rigidities which, on extrapolation to the atmospheric boundary, extend from the value of atmospheric cut-off rigidity to some maximum value determined by the procedure of identifying the particles. If these lower and upper limiting values for protons are denoted by R_a (p) and $R_m(p)$, the total intensity of observed protons ΔI_p will be defined by the expression

$$\Delta I_p = \int_{R_a(p)}^{R_c} \Phi\, dI_p + \int_{R_c}^{R_m(p)} dI_p \qquad (9.5)$$

at

$$R_a(p) < R_c < R_m(p).$$

Similar expressions could be written for total intensities of deuterons and tritons with notations $R_a(d)$ and $R_m(d)$, $R_a(t)$ and $R_m(t)$.

It can be concluded from these relations that the observed ratio of deuterons to protons $\tilde{\Gamma}_{dp} = \Delta I_\alpha/\Delta I_p$ is related to the ratio at rigidity higher than the given rigidity $\Gamma_{dp}(>R) = (I_{od}/I_{op})$ by the relation.

$$\tilde{\Gamma}_{dp} = \Gamma_{dp}(>R)\,\frac{e^{-\beta R_c}\left(e^{\eta R_c} - e^{\eta R_a(d)}\right)\eta^{-1} + R_0\left(e^{-R_c/R_0} - e^{-R_m(d)/R_0}\right)}{e^{-\beta R_c}\left(e^{\eta R_c} - e^{\eta R_a(p)}\right)\eta^{-1} + R_0\left(e^{-R_c/R_0} - e^{-R_m(p)/R_0}\right)}, \qquad (9.6)$$

where $\eta = \beta - (1/R_0)$

The observed ratios of tritons to protons are related to the ratio $\Gamma_{tp}(>R)$ for the rigidity higher than the given one by similar expression but $R_a(d)$ and $R_m(d)$ are replaced by $R_a(t)$

and $R_m(t)$. Obviously, if each of the parameters $R_m(p)$, $R_m(d)$ and $R_m(t)$ is less than R_c, equation (9.6) or the similar relation for $\tilde{\Gamma}_{tp}$ is simplified.

These values of $\tilde{\Gamma}_{dp}$ and $\tilde{\Gamma}_{tp}$ can be compared with those which are obtained in the absence of the geomagnetic threshold:

$$\underset{\text{without threshold}}{\tilde{\Gamma}_{dp}} = \Gamma_{dp}(< R) \frac{e^{-R_m(d)/R_0} - e^{-R_a(d)/R_0}}{e^{-R_m(p)/R_0} - e^{-R_a(p)/R_0}}. \qquad (9.7)$$

Thus, considering the ratio Φ determined by the formula

$$\Phi_d = \underset{\text{with threshold}}{\tilde{\Gamma}_{dp}} \; / \; \underset{\text{without threshold}}{\tilde{\Gamma}_{dp}},$$

along with the similar expression for tritons, it is possible to get the measure of cut-off rigidity.

Value of $\Gamma_{dp}\ (> R)$ is related to the ratio $\Gamma_{dp}(> \varepsilon)$ at energy per nucleon higher than the given one by the equation:

$$\Gamma_{dp}(> \varepsilon) = \Gamma_{dp}(> R) \exp\left[-\frac{\pi}{R}\left(\frac{A_d}{Z_d} - \frac{A_p}{Z_p}\right)\right], \qquad (9.8)$$

where $\pi = \left\{\varepsilon_a(d)\ [\varepsilon_a(d) + 2m_0c^2]\right\}^{1/2}$ and A_d and Z_d are the mass and charge numbers for a deuteron. Similar expression is applicable also for $\Gamma_{td}(> \varepsilon)$ on replacing $\varepsilon_a(d)$ by $\varepsilon_a(t)$ and A_d, Z_d by A_t, Z_t respectively.

In order to apply the above relations to a particular event, one of the piles of photoemulsions meant for studying solar cosmic rays was exposed over Minneapolis on July 18, 1961. This pile drifted in the stratosphere during 1535-1750 UT at an altitude with average residual thickness of the atmosphere equal to 6 g/cm^2.

Protons and α-particles, generated by a solar flare and recorded by photoemulsion, were studied earlier by Freier [10]. It followed from these measurements that β=7.3, R_c = 0.80 Gv and R_0 = 0.16 Gv. It may be mentioned that, according to the observation of Freier and Waddington [I. 28], in the rigidity range of interest in this experiment, the intensity of solar particles was at least by two orders more than the intensities of corresponding quiet beam of cosmic ray particles whose effect can be neglected to a large extent.

The emulsions were thoroughly studied along the line 1 cm below the edge of tracks of particles having zenith angle $< 26^{\circ}$ and azimuthal angle $< 4.5^{\circ}$. Such a selection of tracks was necessary in order to get the residual region at least about 2 mm on the reference line. As a result, values of 0.45, 0.63 and 0.97 Gv were obtained for $R_a(p)$, $R_a(d)$ and $R_a(t)$ respectively whereas the values of 102, 69 and 54 Mev/nucleon were obtained for energies $\mathcal{E}_a(p)$, $\mathcal{E}_a(d)$ and $\mathcal{E}_a(t)$ respectively.

As mentioned above, the selection of tracks also facilitated elimination of tracks with grain density less than 20 grains/100 μ although the procedure, in the long run, assumed that only tracks with density more than 22 grains/100 μ should be taken into consideration. The values obtained for $\mathcal{E}_m(p)$, $\mathcal{E}_m(d)$ and $\mathcal{E}_m(t)$ were equal to 174, 154, and 147 Mev/nucleon respectively. From this, we get the value 0.60, 1.12 and 1.65 Gv for $R_m(d)$ and $R_m(t)$ respectively.

Each particle was studied by measuring the ionization, i.e., the grain density at the scanning line. Its path was traced down the emulsion till the particle stopped or up to the point where the particle gave rise to nuclear fission, left the pile or got reflected in the opposite direction. These latter particles along with those which originated during interactions below and above the scanning line and those which gave rise to interaction above the scanning line were not taken into consideration as they were assumed to be secondary particles. Out of the remaining 162 tracks, 16 were easily identified with tracks of α-particles, and the remaining 146 corresponded to particles with Z=1 (130 of these stopped in the emulsions).

As a result of this processing the values $\tilde{\Gamma}_{dp} = 3.16 \times 10^{-2}$ and $\tilde{\Gamma}_{tp} = 7.1 \times 10^{-3}$ were obtained.

From the equation (9.6) and the corresponding expressions for the ratio of tritons to protons under the conditions of the given experiment, we get

$$\tilde{\Gamma}_{dp} = 2{,}58\Gamma_{dp}(> R) \tag{9.9}$$

and

$$\tilde{\Gamma}_{tp} = 0{,}252\Gamma_{tp}(> R). \tag{9.10}$$

The value of parameters Φ_d and Φ_t are equal to 5.1 and 4.0 respectively. It can be seen from this that the experiment corresponds to observation of a beam of 700-550 protons. The obtained values of $\Gamma_{dp}(> R)$ and $\Gamma_{tp}(> R)$ are equal to 1.4×10^{-2} and 2.8×10^{-2} respectively.

It follows from the equation (9.8) that $\Gamma_{dp}(> \varepsilon) = 0.101$ $_{dp}(> R)$ for energies higher than 69 Mev/nucleon and $\Gamma_{tp}(> \varepsilon) = 1.78\times10^{-2}$ $\Gamma_{tp}(> R)$ for energies $>$ 54 Mev/nucleon and, therefore, $\Gamma_{dp}(> \varepsilon)$ and $\Gamma_{tp}(> \varepsilon)$ are equal to 1.4×10^{-4} respectively.

All these values should be the upper limits as no corrections have been introduced for generation of secondary deuterons or tritons in the upper atmospheric layers. The presence of secondary particles imposes limitations on the values of the ratios obtained by the above-mentioned method since the intensity of secondary particles cannot be calculated with sufficient accuracy.

Secondary deuterons may be formed during nuclear interactions in at least three different ways. Firstly, according to Cocconi et al. [56] and Butler and Pearson [57], deuterons with energy approximately equal to that of the bombarding proton may be formed as a result of semielastic impacts with quasideuterons in nuclei. Secondly, the high-energy tail of the process of nuclear evaporation gives rise to deuterons with energy slightly less than that of the bombarding proton. Thirdly, deuterons will be produced during nuclear collisions of α-particles mainly in the form of fragments of the bombarding α-particles.

The relative role of these effects depends upon such parameters as rate of fragmentation and rate of generation which at present are not known correctly. Even then, making use of the best available values and assuming that the generation is totally caused by solar cosmic rays, i. e., neglecting the role of galactic particles, it can be expected that the value of $\Gamma_{dp}(>R)$ for secondary deuterons is of the order of $1.5x10^{-2}$. Thus, the results of this experiment testify to the absence of deuterons in solar cosmic rays because of which the above-obtained value for $\Gamma_{dp}(>\mathcal{E}) = 1.4x10^{-3}$ is the upper limit.

In the case of tritons, calculation of the expected role of secondary particles is still more uncertain since, as a matter of fact, nothing is known about the values of the required parameters. Even then, it is clear that one particle can always be of secondary origin. Therefore, the above obtained value of $\Gamma_{tp}(>\mathcal{E})$ should be considered to be the most probable value only as the upper limit.

At present, only three experiments dealing with measurement of the composition of solar cosmic rays are known.

The first one was particularly devoted to the study of the problem of probable absence of Be and B nuclei (nuclei of L group) in solar cosmic rays. According to photoemulsion measurements conducted by Biswas and Fichtel [36] on geophysical rockets during November 12 and 15, 1960 flares, not less than 100 heavier nuclei with $\mathcal{E}_k > 43$ Mev/nucleon were observed for every L-nucleus. This result allows us to assure that heavier nuclei passed through the substance (hydrogen) layer > 0.15 g/cm^2 (10^{23} atom/cm^2) from the time when their energy increased to a few Mev/nucleon till their measurement. Independent estimates of Biswas [I. 57] from the same data showed that the mean free path cannot be more than 0.1-0.2 g/cm^2.

The second experiment consisted of the observations of Fireman et al. [30], Tilles et al. [31] and Flamm et al. [58] who, with the help of radiochemical methods, detected noticeable amount of tritium in the casing of the satellite "Discoverer-17" after its irradiation by particles generated during November 12, 1960 flare.

It was shown by the authors [30, 31] that the observed amount of tritium was considerably more than that expected due to local nuclear fissions in the material of the satellite casing.

This conclusion was doubted upon by, for example, Lal et al. [I. 29]. Possibly, the value $\Gamma_{tp}(>\mathcal{E}) = 4x10^{-3}$ obtained in [30, 31] is the upper limit of the actual value at energies > 30 Mev/nucleon. This assumption is confirmed by the fact that the value $\Gamma_{tp}(>\mathcal{E}) = 5x10^{-4}$, obtained by Waddington and Freier [I. 28], does not agree with the above-mentioned value [30, 31] even on taking the difference of energy ranges into account.

It is seen from equation (9.8) that, if R_0 is taken to be the same for two flares (which assumption, as known earlier, has no basis), it is possible to get $\Gamma_{tp}(>\mathcal{E} = 30$ Mev/nucleon$) = 4x10^{-3}$ or $\Gamma_{tp}(>R) \approx 8x10^{-2}$ in place of the observed value $\Gamma_{tp}(>R) \lesssim 2.8x10^{-2}$. Nevertheless, if three tritons had been recorded in place of one and if all the three tritons had been the primary ones, then there would not have been any contration that though the comparison given here is absolutely for different flares, as is well known, there is a considerable difference in the composition of solar cosmic rays for different flares. For example, the observed values of $\Gamma_{\alpha p}(>R)$ in different cases change at least from 1.0 to 0.03. Hence, it is natural to think that such changes are observed for $\Gamma_{tp}(>R)$ as well. During November 12, 1960 flare, the ratio $\Gamma_{\alpha p}(>R)$, according to the measurements made by Biswas and Fichtel [36] and Ney and Stein [I. 82], was approximately equal to 1.0 while in July 1961 Freier [10] obtained a value of about 0.17.

As already known, deuteron does not differ from α-particles in rigidity. Therefore, it can be expected that the tendency to change the ratio should be observed for $\Gamma_{dp}(>R)$ and possibly for $\Gamma_{tp}(>R)$ as well since tritons are subjected to the effect of magnetic field to a lesser extent than α-particles. This effect could satisfactorily explain the divergence between the results of Waddington and Freier [I. 28] and measurements on the satellite "Discoverer-17" [30, 31, 58].

Measurements made by Schaeffer and Zahringer [I. 56] represent the third and the last experiment described here. The authors [I. 56] detected a large relative amount of He^3 nuclei in the material of the same satellite "Discoverer-17". The interpretation of the obtained data is not unique owing to the difficulties in introducing the necessary corrections for the generation of secondary particles. The authors [I. 56] confirm that the ratio $He^3/He^4 = \Gamma_{He^3/He^4}(>\mathcal{E}) \sim 0.2$ and that this value is probably correct with an accuracy up to a multiple of 3. Biswas [I.57], however, puts forward arguments facilitating the assumption that the actual value of this ratio is most probably less than 10^{-2}. The reason is that Schaeffer and Zahringer measured the concentration of He^3 at large depths in the substance. If most of the recorded particles are primary, the concentration of He^3 obtained in [I.56] is certainly high since the effect of the sharp energy spectrum must predominate over the effects of the change in geomagnetic cut-off during satellite displacement, i.e., the flux of He^3 should rapidly decrease with depth. Moreover, the number of He^3 nuclei in this experiment corresponds to the flux which according to Biswas et al. [28], apparently is 10 times the flux of helium nuclei in the energy range of 40-105 Mev/nucleon, namely $4x10^7$ $cm^{-2}.sec^{-1}$. Most probably, because of these differences, at present, there is no point in assigning a particular value to He^3/He^4 ratio.

Stable quantities of tritium and He^3 nuclei in the solar atmosphere are not known but they must be significantly less than those obtained in the above-mentioned experiments. Consequently, in order to explain the presence of considerable amount of these particles, it is necessary to find out certain mechanisms of their generation. At the first glance, the most reasonable explanation results in the assumption that these nuclei are fragments of high-energy α-particles and heavier nuclei generated in nuclear, interactions during their transmission through the solar atmosphere and the interplanetary medium. The effect of heavy nuclei can essentially be negelected since their abundance with respect to α-particles is only about 2%. Thus, the fragmentation of α-particles in the medium, mainly consisting of hydrogen, is a possible process of generation of He^3.

The amount of substance which α-particles must pass through in order to give $\Gamma_{tp}(>\mathcal{E}) \sim 4x10^{-3}$ was estimated by Biswas [I.57]. These estimates give the lower limit $\sim$ 1.3 g/cm^2 ($8x10^{23}$ $atom/cm^2$), which, with great probability, can be increased by 5 times. Similar estimates of Fireman et al. [30] give a value of about 10 g/cm^2. These values apparently do not agree with the results obtained on L-nuclei. Moreover, the expected value of $\Gamma_{dp}(>\mathcal{E})$ must be of the order of $8x10^{-2}$ in place of the actually observed value $\lesssim 1.4\mathrm{x}10^{-3}$. The difference is too large to be explained by the mechanism which leads to a change in $\Gamma_{dp}(>R)$ by 6 times for the two flares under reference. Nevertheless, if the mean free path is less than 0.15 g/cm^2 as it follows from the absence of L-nuclei, $\Gamma_{dp}(>\mathcal{E})$ must be $6\mathrm{x}10^{-3}$ It contradicts the observed limits if one considers the difference in flares. It is clear from this that it is not possible to explain the above-obtained ratios only by fragmentation process.

To this end, Fireman et al.[30] put forward the assumption that the observed nuclei of H^3 and He^3 originate as a result of thermonuclear reactions in the solar atmosphere near the region of the flare. On the basis of the measurements on the relative amount of isotopes of H^3 and He^3 in the casing of the satellite "Discoverer-17", Flamm et al. [58] showed that the amount of H^3 and He^3 is by two orders higher than the value which can be explained by fission of the casing material. From this as well as from the data on fluxes of protons and α-particles during November 12, 1960 flare event, it follows that H^3 and He^3 could have been formed in the chromospheric flare as a result of the reactions $He^4(p,2p)H^3$, $He^4(p,pn)He^3$ and $He^4(p,d)H^3$.

The reactions as suggested above would also lead to the presence of deuterons whose amount is comparable or more than the content of tritium although cross section of the corresponding processes is not known. Deuteron can be generated in the reactions $H^1(\alpha,d)He^3$ with cross section $\sigma \sim 25$ millibarn at an energy of 30 Mev and is destroyed by the secondary reaction $H^1(\alpha,pn)H^1$ with cross section $\sigma \approx 250$ millibrarn. Tritium can be formed in the reaction $H^1(\alpha,tp)H^1$ at $\sigma \approx 10$ millibarn and is destroyed in the reaction $H^1(t,n)He^3$ at $\sigma \approx 250$ millibarn.

As a result of these reactions, it would be possible to get $\Gamma_{dp}(>\mathcal{E} = 30$ Mev/nucleon$) = 10^{-2}$ at $\Gamma_{tp}(>\mathcal{E} = 30$ Mev/nucleon$) = 4\mathrm{x}10^{-3}$. Consequently, $\Gamma_{dp}(\mathcal{E} = 69$ Mev/nucleons$)$ must be of the order of $5\mathrm{x}10^{-3}$. If the observed differences in $\Gamma_{\alpha p}(>R)$ for the two flares under reference are taken into consideration, these values, though more than the observed limit of $\Gamma_{dp}(>\mathcal{E}) \sim$ $\sim 1.4\mathrm{x}10^{-3}$, are not large.

The nature of the above-mentioned nuclear reactions is not fully clear. It is however known that these reactions are extremely endothermic and have thresholds of about 20 Mev. From this, it becomes necessary that, if the reactions are of thermonuclear nature, the local temperature should be more than $10^{11}\,^{\circ}K$. Obviously, such reactions are possible in the region of the flare where the initial density is sufficient to stop the acceleration of α-particles and heavier nuclei due to ionization losses which are more than the increase in energy, and where protons can get accelerated and give rise to nuclear fissions. If, subsequently, the density in this region decreases, additional acceleration of all the heavier nuclei becomes possible and thus, it is possible to explain the observed results.

After a thorough analysis, Waddington and Freier [I. 28] arrived at the following conclusions:

1. Relative abundances of H^1, H^2, H^3 and He at a rigidity higher than the given one, observed near the Earth during the July 18, 1961 flare, are defined by the following values: $1:1.4\times10^{-2}:2.8\times10^{-2}:0.17$ and $1:2\times10^{-3}:6\times10^{-4}:2.4\times10^{-2}$ at 750 Mev/nucleon respectively (only the upper limits of the ratios are given).

2. The observed upper limit for $\Gamma_{dp}(>\mathcal{E})$ is too low to associate it with the abundance of tritium and He^3 nuclei, which are observed in other experiments if these nuclei originated in the fragmentation process. This conclusion is in agreement with the one based on the observations on mass spectrum for low-charge nuclei.

3. The upper limit of the value of $\Gamma_{tp}(>\mathcal{E})$ for July 18, 1961 flare does not agree with the estimates of other authors for November 12, 1960 flare even though one takes into account the difference in the energy thresholds and characteristics of the flares.

4. The value $\Gamma_{dp}(>\mathcal{E}) \lesssim 1.4\times10^{-3}$ is in agreement with the assumption made by Fireman et al. [30] about the thermonuclear processes in the acceleration region of the flare on taking into consideration the obvious difference in the above-mentioned flares. Nevertheless, the physical processes, related to generation of particles, are not still very clear.

It should be pointed out that there would have been no necessity to consider the above-explained nuclear reaction had the actual ratios been noticeable less than the upper limits obtained here.

In order to understand the complicated processes in solar flares, it is necessary to correct the values of Γ_{dp} and Γ_{tp} by recording solar cosmic rays over the atmosphere (to reduce the rate of recording particles) with the help of detectors having high permissible masses and by taking into consideration the geomagnetic cut-off rigidity. In this experiment, the effective cut-off threshold and form of the spectrum can and must be measured by one and the same detector or in any case, at the same time. The other ratios of the type $\Gamma_{\alpha p}$ and Γ_{LM} should also be measured for the same events.

9.4 Increase in the intensity of heavy nuclei. It was shown in the previous Section that the relative charge composition of solar particles, in general, reflects the abundance of corresponding elements on the Sun. This fact indicates that the mechanism of acceleration of heavy nuclei, put forward by A.A. Koschak and S.I. Syrovatskii [59], is not effective on the Sun. On the other hand, the group of research workers under the guidance of L.V. Kurnosova [I. 20; 60] observed for the first time a short-lived increase in the intensity of mainly heavy nuclei ($Z \geqslant 15$) during the flights of Soviet cosmic rockets and satellites (1959-60). The flux of protons in these cases practically did not change. Similar events were also recorded on the satellite "Elektron-2", some of which, according to L.V. Kursonova et al. [61], were accompanied by flares of solar X-ray radiation.

Observations on satellites "Elektron-2" and "Elektron-4" also helped to detect the increase in the flux of nuclei with $Z \geqslant 15$ of duration ranging from a few hours to a few days. One of such events is described by A.A. Suslov and I.P. Tindo [62] (also see the work of L.V. Kurnosova et al. [63]).

The authors [I. 20, 60-63] made the assumption that the observed effects are related to the appearances of solar activity, namely, to chromospheric flares.

It is interesting to mention that the nuclei of H group ($Z \geqslant 10$) carry about 3% of the total flux of nucleons in galactic cosmic rays. Therefore, an increase in the intensity of such nuclei by one order will correspond to a significant increase in the total flux of nucleons. If the energy of additional flux of nuclei is sufficiently large, an attempt can be made to find out simultaneous effects in ground measurements. Such an attempt was made by B.M. Vladimirskii [64] who analyzed the data of world network of stations on nucleon composition of cosmic rays (two-hour values, corrected for barometric effect were used) for the cases of increase in the flux of H-nuclei during 1959-60 (Table 9.6).

The first four flares on September 12-13, 1959 were selected for study. The events 5 and 6 occurred at a time when, after the commencement of magnetic storm the intensity of cosmic rays changes and this makes it very difficult to observe small effects. The analysis showed that, in the case of flares 1 and 2, a significant increase in the intensity which is much more than the statistical error of ± 0.2% is observed in the shock zones. An increase is observed in flare 3 as well but with a less degree of certainty. The effect of flare 4 on the Earth's surface is absent which is fully understandable when we consider the small amplitude of the corresponding increase in the intensity of heavy nuclei.

Owing to the absence of data, it was not possible to explain the presence of similar effects in the meson component (there were only two stations within the limits of the shock zone for the event 2 — Ottawa and Huancayo).

Due to small increases, it was practically impossible to evaluate the energy spectra of the nuclei. However, since the effect was observed at the station with vertical cut-off rigidity of 12 Gv, the spectrum should obviously be extended much above 5 Gev/nucleon. On the other hand, no effects were observed in the solar ionosphere on September 12, 1959 from which it follows [64] that the intensity of nuclei $Z \geqslant 15$ during the flare in the energy range 35-40 Mev/nucleon was apparently not more than $\sim 3 \times 10^{3}$ cm^{-2}, sec^{-2}, $sterad^{-1}$. It should be noted that the measurements [I.20; 60] were taken at $\varepsilon_k > 500$-600 Mev/nucleon and that the flare corresponded to an intensity of about 5×10^{-4} cm^{-2}, sec^{-1}, $sterad^{-1}$.

TABLE 9.6

Serial No.	Date	Time, UT	Duration, min.	Amplitude, number of times	Remarks
1	September 12, 1959	11.27	17	11.8 ± 3.7	Increase for $Z \geqslant 15$; protons were not detected
2	September 12, 1959	12.57	13	6	
3	September 12, 1959	15.23	25	4	
4	September 13, 1959	07.07	7	1.5	Increase for $Z \geqslant 2$; protons were not detected
5	August 20, 1960	07.40	4		No effect for $Z \geqslant 15$; protons absent
6	December 1, 1960	11.20	12	2.8	Increase for $Z \geqslant 12$-14

The small increases in the intensity of nucleon component observed by Vladimirskii et al. [64] are very much similar to the small effects of chromospheric flares detected by Freier [I. 7] and thoroughly studied in subsequent years (see Chapter II). Therefore, it is necessary to explain if the observed increases are related to chromospheric flares. Since the analysis [64] was done on the basis of two-hour data on intensity, the effects observed on ground might not be related to nuclear flares. On the other hand, comparison with flares, made by L. V. Kurnasova et al. [I. 20], is not very satisfactory since the authors [I. 20] considered the time taken by particles to cover the distance between the Sun and the Earth to be approximately equal to zero and tried to compare the obtained data with radio outbursts in the meter band during the development stage of noise storms. As applied to the given case, it is important to mention that (1) the increases in the intensity of cosmic rays due to chromospheric flares, recorded at the sea level, in stratosphere and outside the magnetosphere always lag behind the time of commencement of chromospheric flares by $\gtrsim$ 10-60 minutes and the delay does not depend on the size of the effect; (2) independent of magnitude of the flare, the effect in cosmic rays is observed only in the case when there is an ionospheric effect (i.e. when the flare emits X-ray radiation $\lambda \lesssim 8Å$). This latter phenomenon is, as a rule, accompanied by radio outburst in the centimeter range.

Considering these facts, a whole complex of solar and geophysical data for each of the cases mentioned in Table 9.6 was studied in [64]. A thorough analysis showed that out of all the effects given in Table 9.6, only the August 20, 1960 flare event can be, with a significant degree of certainty, related to the chromospheric flare. Moreover, it is the only event when an increase in the intensity of protons was observed. Out of the remaining five events, noticeable H_α-activity was not observed at all in two cases, in the other two cases, subflares were observed and in one case there was a flare of class 1. Ionospheric effects were observed in none of these cases.

Thus small increases were observed by Vladimirskii et al. [64] at sea level with the maximum amplitude for only two nuclear flares and these increases are undoubtedly related to nuclear flares, since there were no solar flares during this period. The effects were observed only in the shock zone and consequently, the Sun is the source of accelerated nuclei. Increases in the flux of heavy nuclei differ from the usual effects of cosmic ray flares due to abnormal nuclear composition and absence of low-energy particles. The increase recorded on August 20, 1960 is most probably the effect of the flare. All the remaining cases have very poor relation with flares. It can be assumed that they are principally new effects related to some other phenomena of solar activity (quick processes). There is a mention of such effects in literature (see the work of Koshiba and Schein [65]). For example, Ney and Thon [66] and Yngve [67] sporadically observed the daily effect of heavy nuclei. A careful and special study of the data of ground measurements will also possibly reveal such effects. Attention should be paid, for example, to the unusual effect observed by Gill et al. [68] on June 19, 1958 - an intensive increase in meson component near the equator at a hill station Gulmarg. In order to relate these effects to solar activity, a detailed comparison with radio data by using the spectral characteristics of radiation along with the study of the data of optical observations have to be undertaken.

Short-lived increases in the flux of nuclei with $Z \geqslant 15$ at 2200 UT on January 31, 1964 and at 0215 UT on February 14, 1964 of duration of about 16 minutes are mentioned in the work of L.V. Kurnosova et al. [61]. Both the effects were observed when the satellite "Elektron-2" was at a distance more than 6.6×10^4 km from the Earth. The ground observatories did not record any active processes on the Sun during this period but the X-ray detectors aboard the satellite "Elektron-2" recorded two X-ray flares in the range of 2-10 Å which lasted for about 60 and 30 minutes respectively (Fig. 9.5). On January 31, 1964, an increase in the flux of nuclei was recorded 2 minutes before the X-ray flare while the opposite picture was observed on February 14, 1964. As the memory in the satellites takes record once in every two minutes, the corresponding times are known with an accuracy of 2 minutes. Therefore, it can be considered that the increase in the flux of nuclei and the flares of X-ray radiation were recorded practically simultaneously.

Owing to the small dimensions of the Cerenkov detector, the number of nuclei with $Z \geqslant 15$ at the time of the increase in

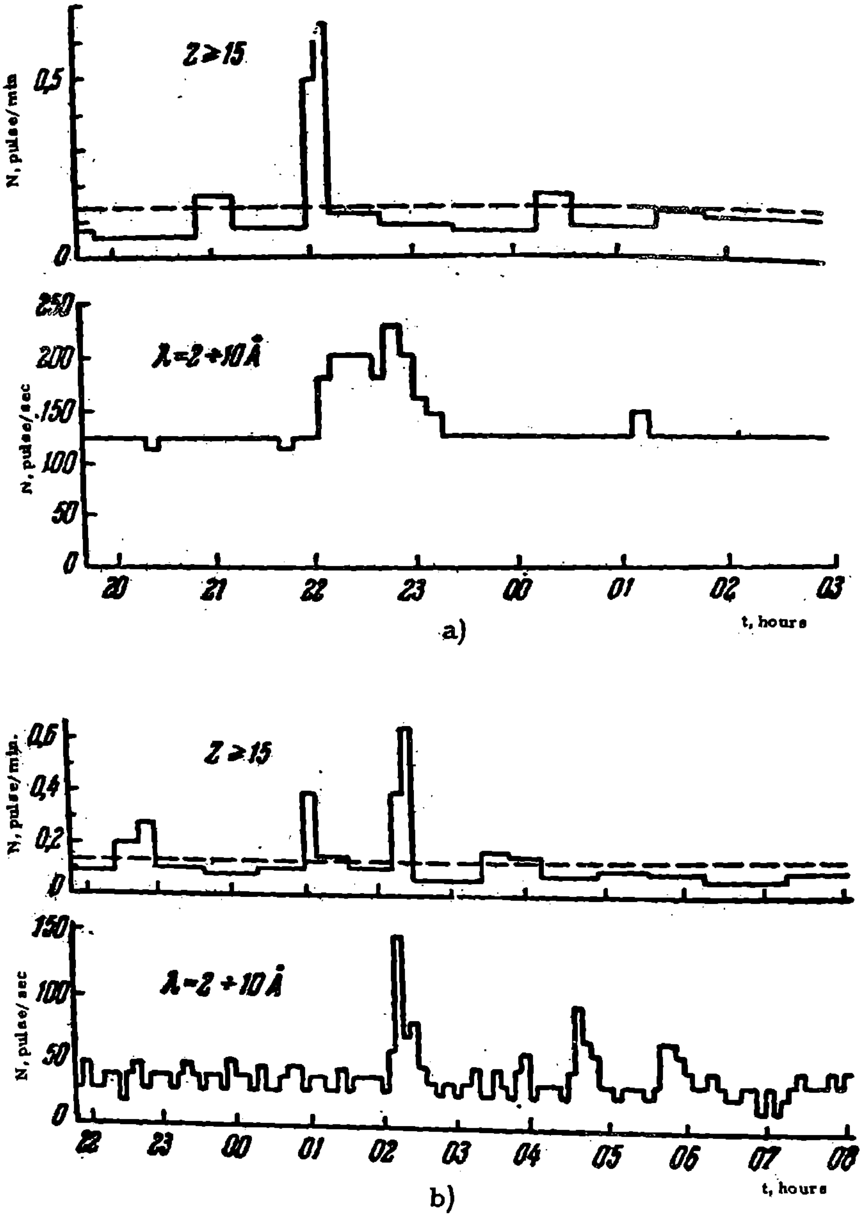


Fig. 9.5. Increase in the flux of nuclei with Z ≥ 15 and flares of X-ray radiation of the Sun in the range λ = 2-10 Å [61].
a) January 31, 1964; b) February 14, 1964.

their flux was not large. Hence it is necessary to estimate the probability of an arbitrary increase in the counting rate of the detector due to statistical fluctuation whose value is comparable to the observed increase. In both the cases under reference, the increase is characterized by transmission of 8 nuclei during $t \leq 16$ min at an average counting rate of 0.14 nuclei/min. According to the estimates [61], the probability of recording of more than or equal to 7 nuclei is of the order of 8.2×10^{-2}. Thus, there is a basis to consider that some of the observed events were not caused by statistical fluctuations.

It is also possible to estimate the probability of arbitrary coincidence of the short-lived increase in the flux of nuclei and the flare of X-ray radiation.

X-ray flares which increased the counting rate by 100 pulse/sec were recorded, on an average, once in every 20 hours during the period under reference. If the total duration of the increase in the flux of nuclei (~ 16 min) and duration of the time of growth of the X-ray flare ($\lesssim 2$ min) is taken as the permissible time, the number of arbitrary coincidences will be 0.1 during 16 days. The probability of recording the two coincidences at such an average number is equal to 4.7×10^{-3}

This estimate along with the conclusion about the non-statistical nature of the short-lived increase in the flux of nuclei makes it possible to consider the assumption [61] about the relation between the increase in the flux of nuclei and outbursts of X-ray radiation of the Sun to be true.

Increase in the flux of nuclei on February 23, 1964, recorded on the satellite "Elektron-2", is reported in the work of A.A. Suslov and I.P. Tindo [62]. The flux of nuclei with $Z \geqslant 15$ increased by $42 \pm 14\%$ as compared to the value on February 20, 1964 whereas the increase in the flux of nuclei with $Z \geqslant 2$ and $Z \geqslant 5$ did not go beyond the measurement errors. According to S.N. Vernov et al. [69], no significant effect was observed in the proton component of cosmic rays.

The period under reference is characterized by a high degree of solar activity. Most of the heliophysical phenomena during this period are related to the radio-emitting region which is denoted by R-7161 in the catalogue [70]. Spots in this region appeared on February 21 and developing rapidly they, by February 24, occupied more than 500 millionths part of the area of the solar hemisphere. In this region most of the chromospheric flares as well as the ejection of matter (on February 23, 1960) were observed during the period February 21-26, 1964. Thus, one can assume that the increase recorded on February 23, 1964 is related to the generation of heavy nuclei on the Sun. The significant increase in the flux of X-ray and radioemission of the Sun on February 23, recorded by I. P. Tindo [71] and also mentioned by Neupert [72] draws particular attention. Moreover, a number of X-ray flares were recorded on February 23-24 by the equipment on board the satellite "Elektron-2" [71] and also according to Kreplin [73], by the American satellite "SR-IV". Therefore, a "thorough" structure of the February 23, 1964 effect is considered in [62]. The effect consisted of eight independent increases in the flux of nuclei with $Z \geqslant 15$ with an amplitude going beyond the limits of one or a few measurement errors. It is shown that the probability of recording all the eight increases (statistical fluctuations) during the whole of the observation time amounting to 2640 minutes, is of the order of 5×10^{-2}.

Thus, it can be assumed that at least some of the observed increases are nonstatistical in nature. This assumption is strengthened by the fact that some of the increases in the flux of nuclei coincided with outburst of X-ray radiation. However, since a number of X-ray outbursts were recorded during the period under reference, it is important to estimate the probability of arbitrary coincidences of the increases in the flux of nuclei with $Z \geqslant 15$ with X-ray outbursts. This probability was found to be low ($\lesssim 1.5 \times 10^{-5}$) and thus, the assumption about the arbitrary coincidence of all the increases in the flux of nuclei and X-ray outbursts can practically be neglected.

Lastly, it may be mentioned that the most appropriate case of the increase in the flux of nuclei with $Z \geqslant 15$ coincided with class 1 chromospheric flare which began at 0645 UT on February 23, 1964 (the flux of nuclei started increasing at 07.00± minutes). The error in the determination of the beginning of the increase (±4 min) is related to the operation of telemetric system since at the given branch, inquiry period of the accumulated information was of the order of 8 min. The probability of arbitrary coincidence of the two phenomena in the given case is less than 10^{-5}.

The above-mentioned estimates facilitate interpretation of the events, recorded on February 23-24, 1964. The events recorded are the increases in the flux of nuclei with $Z \geqslant 15$ (or at least a part of them). The nuclei are generated on the Sun during a flare event with only heavy nuclei escaping beyond the limits of the solar atmosphere and also as a result of retarded radiation of electrons similar to that shown in the work of L. V. Kurnosova et al. [16] for the cases of short-lived increases.

Important results on the measurement of nuclei with $Z \geqslant 2$, $Z \geqslant 5$, $Z \geqslant 15$ ("Elektron-2") and $Z \geqslant 20$ ("Elektron-4") during January 30, 1964 — February 9, 1965 are summarized in the work of Ya. L. Blokh et al. [74]. In addition to modulation phenomena, cases of the increases in the flux of heavy nuclei were observed during this period. Almost a sudden increase on August 20, 1964 in the channel with $Z \geqslant 20$ (Fig. 9.6) was the most significant observation. During the subsequent 10 days, the intensity decreased gradually and remained higher than the average value for the period July-first half of August.

Significantly a low increase ($3.5 \pm 1\%$ during 10 days as compared to $54 \pm 10\%$ for $Z > 20$ nuclei) was observed in $Z \geqslant 5$ channel; at the same time, even some decrease in the flux of nuclei was observed in $Z \geqslant 2$ channel. If the role of $Z > 20$ nuclei is eliminated from the counting rate in $Z \geqslant 5$ channel, we obtain some increase in $Z \geqslant 5$ channel which goes beyond the limits of statistical measurement errors. According to the measurements of S.N. Vernov et al. [69] on the same satellites, an increase of the order of 1% was observed in the proton component. Data obtained during August 20-30, 1964 from the ground network of stations, also showed some increase which is difficult to explain by modulation effects. In its energy and time characteristics, it considerably differs from the increases in the flux of nuclei and protons observed during solar flares near the maximum of solar activity [I. 24].

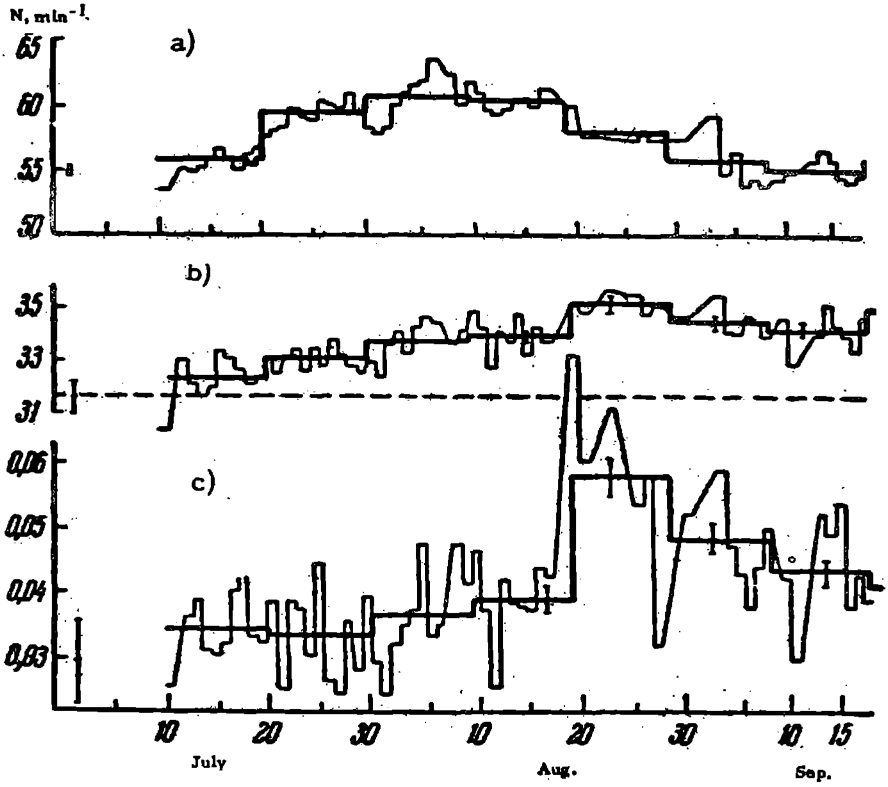


Fig. 9.6 *Data of 'Elektron-2" and 'Elektron-4" [74] on the measurement of flux of nuclei in July-September, 1964.*
a) $Z \geqslant 2$; b) $Z \geqslant 5$; c) $Z > 20$ (thin lines). Thick lines - average values of the counting rate during 10 days. Statistical errors are shown on the left.

During the August 20, 1964 event, mainly the flux of extremely heavy nuclei increased while in the events described in [I. 24], protons contributed maximum to the additional flux of cosmic rays. Another difference lies in the extremely slow decrease in the flux of heavy nuclei with the passage of time. In spite of these differences, there are some indications to assume that the August 20, 1964 effect was caused by the processes on the Sun with predominant acceleration of heavy nuclei while the generation of nuclei in this case was obviously related to some comparatively sudden heliophysical phenomenon observed on August 19, 1964. The month of July 1964 was characterized by the minimum solar activity. A few class 1 flares were observed in August (including the one on August 19). In contrast to other days, a sufficiently powerful outburst of radioemission of type III on frequencies of 23-111 MHz was recorded on August 19. This rare phenomenon was the only case during the period April-November 1964. Moreover, the ejection of matter was observed for a few hours on August 19 from the same region of the Sun where the flare had taken place. Such ejections on the Sun were not observed from the beginning of the flight of satellite "Elektron-4" till August 19, 1964.

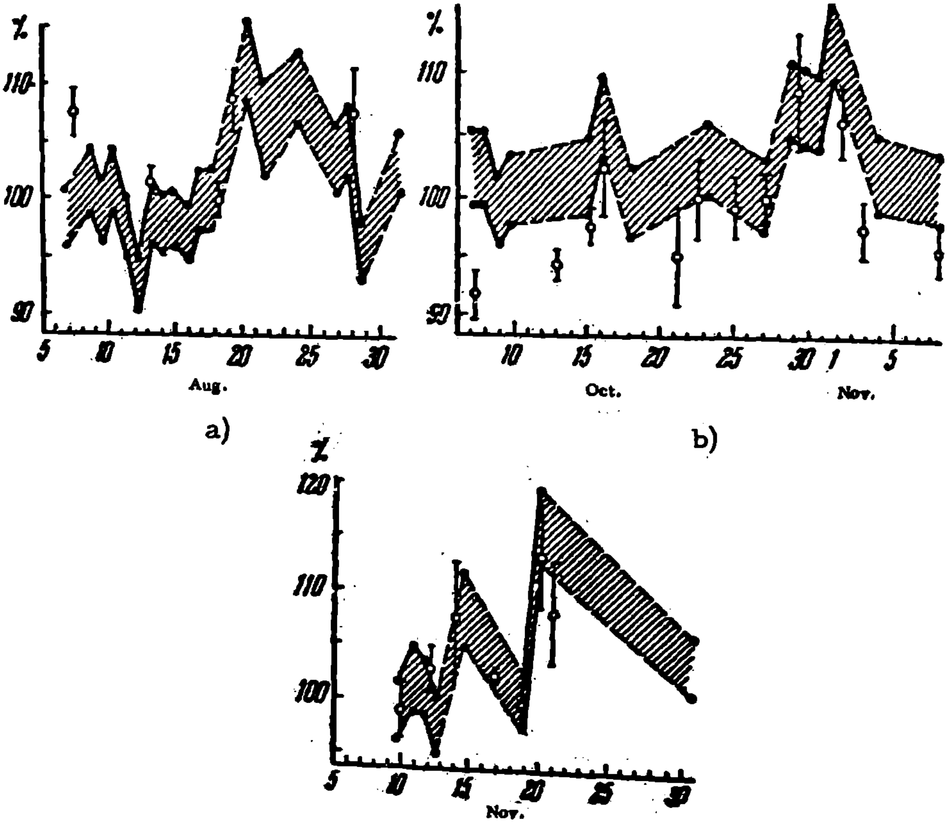
Increases by 14±1% in $Z \geqslant 2$ channel, 7±3% in $Z \geqslant 5$ channel and 32±23% in $Z > 20$ channel were observed from September 28 to November 1, 1964. This event also cannot be characterized as modulation phenomenon since, according to [63, 64], there was no noticeable increase in the flux of protons with $\varepsilon_p \geqslant 50$ Mev during this period. During November 18-19, 1964, the increase in the flux of heavy nuclei was 10±1% ($Z \geqslant 2$), 10±3% ($Z \geqslant 5$) and 80±25% ($Z > 20$). From 2140 UT on November 3, to 0115 UT on November 4, 1964, an outburst of very heavy nuclei was observed. The probability that this increase was caused by statistical fluctuations is $\lesssim 10^{-6}$.

It should be noted that the above-mentioned events have some characteristics common with the short-lived increases in the nuclear component of cosmic rays observed during 1959-60 (predominant acceleration of heavy nuclei, correlation with solar phenomenon particularly with radio outbursts).

Thus, the analysis of increases in the intensity of heavy nuclei facilitates the assumption that, in most of the cases, these effects may be caused not by chromospheric flares but by some other, more rare and unusual processes on the Sun.

B.M. Kuzhevskii et al. [75] made a comparison of the data on the cases of predominant acceleration of heavy nuclei on the Sun, observed by L.V. Kurnosova et al. [63] during the flight of the satellite "Elektron-4", with the results of observations taken by the satellite "Kosmos-25" during the same period on the ionizing capacity of particles. The ionization chamber, filled with argon at a pressure of 8 atmospheres, with a geometrical factor of 1500 cm^2. sterad was used on the satellite "Kosmos-25". The ionization, remaining in the chamber after the passage of a specific number of particles through it, was measured This method facilitated the measurement of integral ionization of primary beam per particle independent of the value of the flux of particles. Integral ionization, measured in this way, depends only on the charge composition and energy characteristics of radiation.

From an analysis of the data of the satellite "Kosmos-25", it became apparent that the ionization recorded by the chamber increases at certain times. In order to compare the chamber data with the measurement results of Cerenkov counter [63], the expected increase in ionization per particle was calculated



a)

b)

c)

Fig. 9. 7. Comparison of the data of Cerenkov counter [63] with the data of ionization chamber [75] (circles) for the cases of the increase in the intensity;
a - August 18-20, 1964; b - October 27-29, 1964; c - November 18-19, 1964. Hatched region shows the expected value of the integral ionization by considering the measurement errors, calculated from the data of Cerenkov counter [63].

on the basis of the data given in [63] (the flux of galactic cosmic rays was taken to be constant). The obtained values of the expected change in the integral ionization are shown in Fig. 9.7 in the form of hatched bands whose width is determined by the measurement errors of Cerenkov counter [63]. Circles show the data obtained by ionization chamber on the satellite "Kosmos-25" for those periods for which data on particles with $R > 4$ Gv were available. A good agreement between results of measurements by different detectors is seen from Fig. 9.7 and there is additional proof of the real predominance of increases in the flux of heavy nuclei recorded in [63].

Before this Section ends, mention should be made of the work of Sakurai [76] in which he compares the relative abundance of solar protons and solar α-particles at constant rigidity $(dI/dR)_p/(dI/dR)_\alpha$ during flares. It is shown that this ratio is 5-50 if the flare is observed before the sudden commencement of a geomagnetic storm and is of the order of 1 if the flare is observed after the sudden commencement. It follows from the measurements of medium and heavy nuclei of solar cosmic rays that their rigidity spectra are similar to the rigidity spectrum of α-particles and the ratio of the number of α-particles to that of these nuclei is almost constant for different cases. Moreover, the abundance of medium and heavy nuclei in solar cosmic rays is the same as on the Sun. A comparison of these data with the characteristics of solar radio-outbursts of type IV facilitates the conclusion that, at the initial stage of acceleration of solar cosmic rays, the rate of acceleration of protons is considerably more than that of heavier nuclei. Obviously, during the initial phase of acceleration, Fermi mechanism is more effective than the betatron mechanism and plasma particles are mainly accelerated by thermal energies.

10. TIME VARIATIONS OF SOLAR PARTICLES

10.1 General characteristic of time variation. Peculiarities of time variation of cosmic rays are of great interest for selecting the model of their propagation in the interplanetary space, for studying time variations of their spectrum and for studying the structure of the interplanetary magnetic field. Experimental data on time variations of the flux and spectrum of solar particles are described in this section on the basis of the observations of different authors for different cases.

As shown in Chapter IV, the rate of change of the intensity of solar particles of a given energy at the Earth's orbit depends on the duration of their emission from the region of chromospheric flare, on the structure and intensity of the interplanetary field between the Sun and the Earth, and on the distances from the Sun which are of the order of a few tens of astronomical units. The study of the properties of isolated regions of interplanetary space, in its own turn, is important for working out a solution to the problem of modulation of galactic cosmic rays.

High-energy solar particles, emitted during chromospheric flares, in some cases, propagate to the Earth along the Sun-Earth direction or slightly westward. It facilitates the assumption that particles propagate along spiral magnetic field whose model for the first time was suggested by Parker [I. 61].

In most of the cases, particles arrive not immediately after the flare but start appearing only after some tens of minutes. In this case, their intensity on the Earth's orbit is almost isotropic and the intensity attains the maximum value only after a few hours. In most of the cases, intensity decreases with the characteristic time of the order of a few hours for relativistic particles and slightly higher for particles of lesser energy. Presence of considerable isotropic flux of particles near the Earth during a long interval of time after the disappearance of the corresponding solar flare is usually interpreted as the result of accumulation of particles in the solar system. Obviously, free exit of solar particles from the solar system is difficult due to the presence of magnetic fields beyond the Earth's orbit.

Delay of most of the solar particles compels us to assume that the particles temporarily accumulate in magnetic fields on the Sun or near the solar surface. Afterwards, the particles, by drifting or diffusion (or under the simultaneous action of both these mechanisms), leave the region of accumulation and propagate to the Earth. Moreover, their intensitv in this case increases very slowly.

The assumption that the particles accumulate in the interplanetary space and not near the Sun is based on a simpler model of accumulation mechanism satisfying the condition of approximate isotropy of the flux of solar particles near the Earth This model should be preferred since it requires a lesser amount of particles to be generated on the Sun for explaining the flux observed on the Sun as compared to the model of solar mechanism of accumulation. This model is simpler because it does not assume the presence of any magnetic fields excepting the ones expected from Parker's theory [I. 61] and measured several times directly in the interplanetary space (see Section 13.2). Moreover, it combines the problem of the delay of arrival of particles and the problem of slow decrease in their intensity into one common diffusion problem.

The decrease in the concentration of high-energy solar particles on the Earth after attaining the maximum value can be described by the power law t^{-s} where s is usually within the limits of 1.0-2.5 or by the exponential law $\exp(-t/T_o)$. The quicker decrease, i.e., decrease according to the exponential law or the power law with $s \geqslant 2.0$, is characteristic of particles with higher energy (more than 10^9 ev/nucleon) and for periods much longer after the beginning of the increase. The decrease in the intensity of particles with lesser energy (10^7-10^8 ev/nucleon) is sometimes very slow. There is nothing surprising in this. It is considered that, in the case of the full spectrum of field irregularities, the diffusion coefficient $\varkappa$ depends on the energy of the particles as well as on the distance from the Sun (see Chapter IV).

In most of the works, the change in the concentration of particles with the passage of time is studied only for one specific energy or a limited interval of energies and therefore, any conclusions about the value and distribution of $\varkappa$ in the space will be applicable only within a limited range of energies.

10.2 Results of the analysis of different cases. Data on flares of solar cosmic rays, recorded up to the end of 1961, were systematically described in L. I. Dorman's books [I. 1; I. 2]. Therefore, in this Section, attention will be paid only to the most important characteristic features of time variation and energy spectrum of solar particles.

Based on the data of neutron monitors, satellites and riometers, Bennet [77] studied the morphology of the increases in the intensity of cosmic rays caused by solar flares. Data on eight events were compared with the power law of decrease in the intensity $\sim t^{-s}$. In the case of five flare increases, the index on the Earth's surface $s = 2.08$ whereas for all the eight cases, on an average, $s = 1.97$. Hence, it is concluded that the power law with $s = 2.0$ reflects well the observed rate of decrease of the concentration of medium- and high-energy particles. The analysis of the dependence of delay of particles on the heliolatitude of flares, according to Bennet [77], confirms the well-known results of the existence of the east-west asymmetry. The time lag considerably decreases (and most probably, with a leap) when the region of flare intersects the central meridian.

Many interesting results were obtained by Winckler and Bhavsar [78] for the September 3, 1960 flare event on the basis of stratospheric measurements. It was the only case during the previous solar cycle when a class 3 flare on the eastern limb of the Sun (helio-coordinates 17°N, 90°E, beginning at 0040 UT on September 3) gave rise to the increase at the sea level as well as in the stratosphere.

The intensity of solar particles in the stratosphere started increasing 83 minutes after the outburst of microwave radio emission. The increase during the first 5 hours can be described on the basis of diffusion coefficient with transport range $\lambda \sim 3 \times 10$ cm. The intensity decreased according to an exponential during about 140 hours after the chromospheric flare with time constant $T_0 \approx 23$ hrs. This result is in conformity with the existence of magnetic barrier at a distance of about 22 astronomical units from the Sun through which the particles go beyond the limits of the solar system.

While studying the same flare, A. N. Charakhch'yan et al. [IV. 63] considered the beginning time 20 hours after the chromospheric flare. In this case, the decrease in the intensity can be described by the diffusion law $\sim t^{-3/2}$ at $\varkappa = 5.5 \times 10^{21}$ $\mathrm{cm}^2/\mathrm{sec}$. Winckler and Bhavsar [78] considered the transition of particles 83 minutes after the optical maximum of the flare, and found that the increase in solar particles is in agreement with the diffusion equation if the injection takes place at the time of the flare. Conclusions of A. N. Charakhch'yan et al. [IV. 63] were based on insufficiently reliable data on the earlier stage of the increase and on the assumption of the power law of attenuation. The data [78] show that the exponential nature of attenuation is a better approximation.

Roederer at al. [22] studied the sequence of heliophysical and geophysical phenomena leading to unusual variations in the intensity of cosmic rays during the period November 10-15, 1960. The distribution of intensity on the Earth's surface during the November 12 cosmic ray flare does not agree with the theory of shock zones which is explained by the action of a magnetic cloud existing near the Earth at that time and causing Forbush effect at 1930 UT on November 12, 1960. This cloud consisted of a strong magnetic field whose lines of force formed the "magnetic trap". Such a field was found to be capable of trapping a large part of high-energy particles originating during class 3+ chromospheric flare 6 hours before the beginning of the Forbush effect. This model allows us to explain the second increase in the intensity of solar particles starting after the Forbush effect.

A detailed analysis of the observations on solar particles, caused by November 12 and 15, 1960 flares, at the stations Thule (Arctic) and McMurdo (Antarctic) situated near the geomagnetic poles, is given in the work of Pomerantz et al. [79]. It is shown that the propagation of fast particles to the Earth on November 12, 1960 was mostly isotropic in nature caused by scattering of particles and magnetic irregularities in the interplanetary space. The analysis of the dependence of amplitude of the increase on the geomagnetic cut-off rigidity showed that particles with rigidity of 1.0-2.8 Gv gave rise to about 85% of the total effect. An estimate of the total energy of solar particles in the given rigidity range gives a value of 2.2×10^{29} erg for the first increase of November 12 and 1.9×10^{29} erg for the second increase. An estimate of the diffusion coefficient in the same range gives values of 3.5×10^{22} and 1.1×10^{22} cm^2/sec for the first and second increase respectively. It is assumed that the increase in the intensity of solar particles was caused by the arrival of a magnetized cloud of solar plasma near the Earth's orbit.

Conforto and Iucci [80] also studied the events in November 1960 based on the data obtained from ground measurements.

Time characteristics for November 12 and 15, 1960 flares were thoroughly investigated in the work of Feiter et al. [81]. The investigations were based on the observations on the intensity of neutron component at four stations having cut-off rigidity less than 4 Gv (Upsala, Niderkhorst, Limeil, Pic du Midi). It was shown that the November 12 flare event consisted of two increases and the second one apparently had a complex nature and can be partly related to the change in the intensity of geomagnetic field. The decrease in the intensity after attaining a maximum value followed the exponential law. Moreover, if for November 12 flare event the period T_0 during which the flux of solar flares decreases by e times was significantly different for different stages (from 1 to 3.5 hours), the value of T_0 for November 15 flare event was the same for all the stages and was equal to 4.5 hours. This points out the directional nature of the flux of solar particles on November 12, and the isotropic nature of November 15, 1960 flux.

Based on the data of world network of stations, it was shown by A. I. Kuzmin et al. [82] that the three outbursts of cosmic rays during November 12-15, 1960 can be related to flares with large time scale. The duration of increase of intensity for the first flare was, on an average for all the stations, 2 hours 40 minutes. The maxima continued for about 2.5 hours, an exponential decrease in intensity with average time characteristic $T_0 \sim 6.6$ hours was observed at stations with geomagnetic threshold $\leqslant 1.3$ Gv. The dependence of T_0 on the energy of recorded particles (see Table 14.1) was detected. A comparison of the profiles of the first increase at Sulfur and Chicago stations shows that, throughout the event, the energy spectrum of solar particles changes continuously and becomes more rigid.

The average duration of increase for the second flare was 1 hour 25 minutes. The flare had a sharp maximum at 2000 UT on November 12, 1960. The characteristic time of decrease $T_0 \sim 3.5$-4 hours.

The duration of increase for November 15, 1960 flare was 1 hour at Yakutsk, Sulfur, Lincoln and Elsvorts stations and 40 minutes at Chicago, Ottawa, Deep River, Resolute and Churchill. After attaining the maximum value, the intensity of cosmic rays did not change for 1—1.5 hrs. It started decreasing at all the stations with an average value of $T_0 \sim 5$ hrs.

Lockwood and Shea [I. 79] showed that differential spectrum of pulses was $D(p) = 5x10^5 p^{-6}$ particle.m^{-2}. sec^{-1}. sterad^{-1} $(Gev/c)^{-1}$ at $1 \leq p \leq 7$ Gev/c for November 12, 1960 flare and $D(p) = 10^6 p^{-6}$ particle.m^{-2}. sec^{-1}. sterad^{-1} (Gev/c) for November 15, 1960 flare.

Data of observations on solar and galactic cosmic rays obtained with the help of satellite "Explorer-7" (altitude of flight 550-1100 km) during the period October 13, 1959 - February 17, 1961 are given in Lin's dissertation [83]. Absolute values of maximum intensities of solar protons with $\mathcal{E} > 30$ Mev have been obtained for 21 flares. It is shown that the decrease in their intensity can be represented in the form $\sim t^{-s}$ where 't' is measured from the commencement of the corresponding solar flare and the value of 's' changes within the limits 1.2-3.4. According to [83], the latitude dependence of the intensity of solar particles at different longitudes for eight large flares can be well described by the Mak-Ilvain parameter L but does not agree with the distribution of geomagnetic threshold rigidities suggested by Quenby and Webber [I. 43]. A comparison of the results of measurements on "Explorer-7" with the data of high-latitude riometers showed that solar protons with $\mathcal{E}_k > 30$ Mev play an insignificant role in the phenomena of absorption in polar caps.

Recording of solar cosmic rays caused by flares on the invisible side of the Sun is of exceptional interest for selecting a suitable diffusion model. As mentioned by Parker [I. 61], the propagation of particles from such flares is very difficult to record as a separate event due to the extremely large time lag, probably going up to one day, and due to their low intensity which is $\lesssim 1\%$ of the intensity of particles from flares on the visible side of the Sun. Nevertheless, there is one extremely interesting case when it definitely became possible to observe the propagation of solar cosmic rays from a chromospheric flare on the invisible side of the Sun. According to Pomerantz and Duggal [84], the flare occurred on November 20, 1960 in the active region with longitude of 120° to the west of the central meridian, i.e., at 30° beyond the edge of the disk. According to observations of Hansen [85], its height over the photosphere, at the time of its appearance over the edge of the solar disk, was 93,000 km. Astronomical observations showed that during this time, the plasma was emitted from behind the disk with radial velocity of about 1000 km/sec. The maximum height of eruptive cut-off was about 300,000 km. An increase in the intensity of cosmic rays was recorded on the Earth's surface and in the stratosphere and the time lag of the particles was of the order of a few hours. Specifically, significant increases in the intensity of neutron component of cosmic rays were observed by Conforto and Iucci [80] at the stations Thule (Arctic) and McMurdo (Antarctic). These increases were of the order of 6.3% and 10.4% respectively. Obviously, the small delay is explained by the fact that the propagation of particles is considerably facilitated by the presence of quasiradial interplanetary magnetic field whose lines of force are bent due to the rotation of the Sun. The November 12, 15 and 20, 1960 flares of cosmic rays are also analyzed in the work of V. I. Ivanov et al. [86].

Anderson [87] once again analyzed the data of riometric observations and ballloon measurements on energetic particles obtained during the end of August 1957. It is shown that during this period there were two outbursts of solar particles and not three as were mentioned earlier by the author. The time lag between the commencement of the flare and the propagation of the particles to the Earth was considerably less than that suggested earlier on the basis of data on solar radio emission. The class 3 flare recorded at 2010 UT on August 28, 1957 is the most probable source of solar particles which started propagating to the Earth after 2140 UT. The experimental data for August 29 event are unreliable. The second outburst of solar cosmic rays, which could be clearly observed, started at 1340 UT on August 31, 1957. The chromospheric flare which started at 1257 UT on August 31, 1957, best corresponds to this event. Anderson arrived at the conclusion that the whole of the complex of helio- and geophysical phenomena, observed during the end of August 1957, can be explained within the framework of the model of "magnetic trap" suggested by Gold and developed by McCracken and other research workers.

10.3 Flares in July 1961. Hofmann and Winckler [88] investigated the July 1961 flares thoroughly on the basis of the data of balloon measurements over Churchill and Minneapolis. Simultaneous observations were made by Keppler et al. [II. 54] over Kiruna (Sweden).

Interesting data on the spectrum of solar protons with $\varepsilon_k = 77.5$-290 Mev during July 12, 1961 flare were obtained by Guss and Waddington [40] with the help of emulsions flown on balloons over Churchill. Differential spectra, averaged for the period 0839-1819 UT on July 13, are described by the power function of kinetic energy with index $\gamma = 5.6 \pm 0.3$, by power function of total energy reduced to potential energy with $\gamma = 47 \pm 3$ and by exponential function for rigidity from $R_0 = 52 \pm 3$ Mv. The intensity of particles with $\varepsilon_k \geqslant 77.5$ Mev was equal to $1.69 + 0.14$ $cm^{-2} \cdot sec^{-1} \cdot sterad^{-1}$. During the July 18 flare, the intensity of particles with $\varepsilon_k \geqslant 100$ Mev was equal to 40 ± 8 $cm^{-2} \cdot sec^{-1} \cdot sterad^{-1}$ during the interval 1305-1918 UT. Similarity between these events and flares of April 29 and May 4, 1960 is noted.

Keppler et al. [II. 54], on the basis of data of balloon measurements over Kiruna (Sweden), studied the four events of injection of solar protons in July 1961. The obtained results are given in Table 10.1 from which it is seen that on decreasing the flux of protons of nonrelativistic energies according to the law $\sim t^{-s}$, the index considerably changes for different events. It was shown for July 12, 1961 event by Keppler et al. in the same work that 10 hours after the chromospheric flare, the spectrum in the range $110 \leqslant \varepsilon \leqslant 270$ Mev was of the type $\sim \varepsilon^{-4.4}$ and that spectrum in the range $110 \leqslant \varepsilon \leqslant 160$ Mev after 5.5 hours became softer: $\sim \varepsilon^{-6.1}$.

As a result of the thorough analysis of the data of balloon measurements with the help of gas-discharge counter and ionization chamber, Hofmann and Winckler [88] arrived at the conclusion that the intensity of solar protons from July 18 and 21, 1961 flares decreased approximately according to the exponential

TABLE 10.1

Data on July 1961 flares [II.54]

Date of the flare	Type of differential spectrum	Energy range, Mev	Value of γ	Law of time variation
July 12, 1961	$\varepsilon_k^{-\gamma}$	100-220	4.4 ± 0.35	-
July 18, 1961	$\varepsilon_k^{-\gamma}$	420-600	7.6	t^{-2}
	$\varepsilon_k^{-\nu}$	290-420	6.2	t^{-2}
	$\varepsilon_k^{-\nu}$	170-290	4.8	t^{-2}
July 20, 1961	$\varepsilon_k^{-\gamma}$	100-400	5.5 ± 0.5	-
July 28, 1961	-	100-600	-	$t^{-0.8 \pm 0.1}$

law $\sim \exp(-t/T_0)$ where T_0 was equal to 8.9 and 5.3 hours for the events of July 18 and 20 respectively.

Commenting on the results of the analysis of Winckler and Bhavsar [78] for September 3, 1960 flare and of Hofmann and Winckler [88] for July 1961 flares, Chasson [89] mentions that exponential law of attenuation was sufficiently clearly detected earlier by Anderson et al. [90] for May 4, 1960 flare. During this flare, the intensity decreased according to the exponential law in the beginning with a time constant $T_0 \approx 17$ min, which afterwards increased to 78 minutes (of course, it should be pointed out that the intensity later on also decreased according to the law $\sim t^{-3/2}$ but the accuracy of measurements during this period was insufficient).

The flare events of July 1961 were also studied by E.V. Kolomeets [91] on the basis of the data on nucleon component for 9 stations. The analysis showed that the decrease in the intensity of solar protons from the July 18, 1961 flare event continued for about 10 hours approximately according to the law $\sim \exp(-t/T_0)$ where $T_0 \approx 15$ min. Almost at all the stations during the first hour after maxima, a very sharp decrease in the intensity was observed after which there was small increase. Most probably, during this time (1230-1330 UT), there was a small solar flare responsible for the additional flux of particles.

The July 20, 1961 increase in the intensity ot solar protons can be related neither to small ($\lesssim 1\%$) nor to large increases. The maximum intensity during this flare attained a value of a few per cents and was slightly more than the limits of statistical errors. The increase in intensity continued for about 30 minutes and the decrease for not more than 2 hours, whereas in all other cases of small as well as large increases, the decrease continued for not less than 8-10 hours. Apparently, during some flares, there are "tunnels" for free exit and propagation of solar particles to the Earth along the lines of force of the magnetic fields "frozen" in corpuscular beams.

Fig. 10.1 shows the dependence of the amplitude of increase on threshold rigidity. It is seen that particles with $\mathcal{E}_{th} \sim 200$ Mev were intensely scattered by interplanetary fields on July 20, 1961 which caused the attenuation of the effect in the region of very high latitudes. It is not eliminated that cut-off from the side of low energies took place even during the exit of particles from the region of solar corona.

With the help of the method of correlation coefficients, E. V. Kolomeets [91] determined the spectrum of solar particles (Fig. 10. 2) which up to energies of 2. 5 Gev can be approximated by the relation $\varepsilon_{k}^{-\gamma}$ where γ is equal to 3. 5-4. 0 and 2. 5-3 for July 18 and 20, 1961 flares respectively.

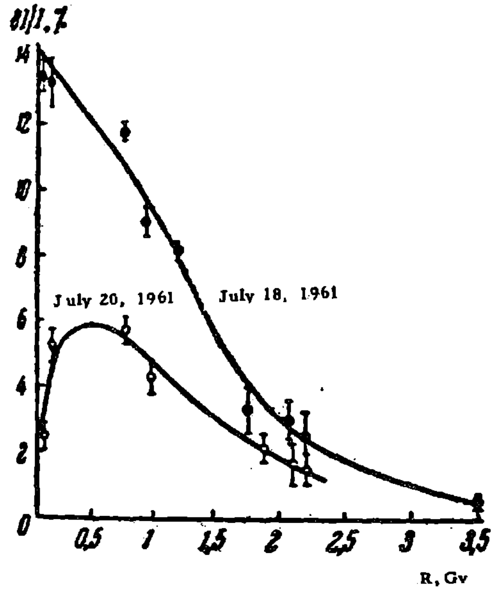


Fig. 10. 1. Latitude effect of flares in July 1961 [91].

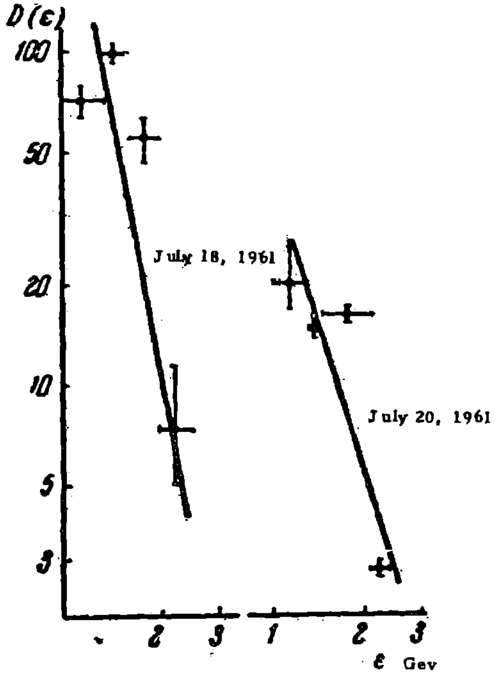


Fig. 10. 2. Energy spectra of solar particles during July 1961 flares [91].

Pomerantz and Duggal [92] analyzed the data on the increase in the intensity of neutron component at high-latitude stations of Thule and McMurdo on July 18 and 20, 1961. Similar increases in July 1961 were studied by Wilson et al. [93] for a number of stations on mountains and at sea level.

Detailed investigations on July 1961 flares were carried out by A. N. Charakhch'yan and T. N. Charakhch'yan [94] on the basis of the data of stratospheric measurements over Murmansk.

The results of eight flights during July 12-20, show that the spectrum of solar particles during this period remained practically unchanged: $\sim \varepsilon_k^{-4}$.

Valuable data on flux of solar particles with ε_k = 1-15 Mev and $\varepsilon_k > 40$ Mev and their variations during July 1961 magnetic storms were obtained by Zmuda et al. [II. 3] from the observations on the satellite "Injun-1" (the satellite was launched on June 29, 1961, inclination of its orbit with the equatorial plane 67°, height in apogee 998 km and in perigee 881 km).

10. 4. Flares during the end of 1961 and in subsequent years. Results of measurements, on satellites "Explorer-12" and "Explorer-14", of four large increases in the intensity of solar protons related to chromospheric flares on September 10 and 28, 1961, November 10, 1961 and on October 23, 1962, are analyzed in detail in the work of Bryant et al. [I. 54]. It is shown that the short-lived fluctuations in the intensity, observed for these cases, are related to the regular structure either of solar wind or of transition region between interplanetary plasma and magnetosphere. Mention is also made of the increase in intensity on September 7, 1961 which is not related to any flare. September 28, 1961 flare is analyzed in detail in Chapter IV. It is appropriate to mention here that five hours after the commencement of September 28, 1961 flare, the intensity decreased according to the law $\sim t^{-2}$. On the basis of the data of the satellite "Explorer-14", Frank [95] detected the April 15, 1963 flare. The time variation of protons with $\varepsilon_k > 23$ Mev for this flare is shown in Fig. 10. 3.

L. L. Lazutin [96, 97] noted an increase in the intensity of cosmic rays in stratosphere over the station Apatite (67°38'N; 33°20'E). Measurements were taken with the aid of radioprobe "RKL-4". The data of 11 flights were analyzed. Increases in the intensity were observed on September 17, 1963 at about 0900 UT and on September 21, 1963 at about 0830 UT. For the latter case, the integral spectrum of protons had index $\gamma = 3.5$ whereas the intensity decreased according to the law $\sim t^{-1.7}$.

An interesting comparison of some satellite and riometric data on solar protons for September 1963 flares is given in the work of Chivers and Burrows [98]. Measurements were

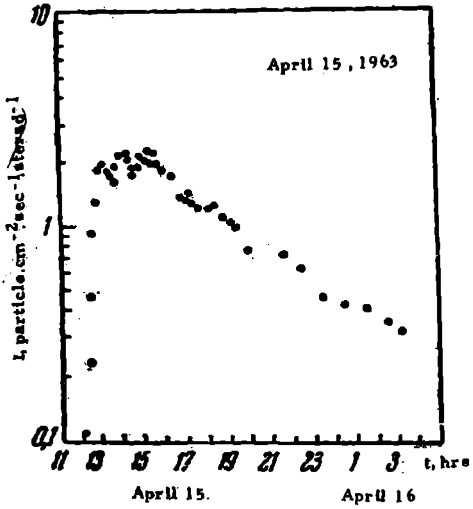


Fig. 10. 3. Time variation of the intensity of solar particles for the April 15, 1963 flare [95].

taken with the help of satellite "Alouette" (height of orbit 1025±25 km, inclination 80°, period of rotation 105 min) and data of riometers at 30 MHz installed at the northern and southern polar caps, were used for comparison.

Two significant increasses of solar cosmic rays were observed in September 1963. The first one followed a series of class 2 flares and was recorded for the first time by satellites and riometers immediately after 0000 UT on September 21, 1963. This increase was also recorded in stratosphere by L. L. Lazutin [96]. The second increase was observed at about 0700 UT on September 26 after class 3 flare.

In order to study the dependence of absorption on the flux of protons, Chivers and Burrows compared the rated values of absorption in the southern hemisphere with the flux of protons averaged for the period of one transition over the northern polar cap. The results of the comparison for protons with ε_{k} =1. 3-7 Mev and $\varepsilon_{k} > 33$ Mev are shown in Fig. 10. 4 where the time sequence of obtained points is marked by arrows. The best approximation is shown by straight lines (full) and these can be compared with the calculation results of Bailey [99] (dotted lines) for protons with $\varepsilon_{k} > 10$ Mev moving vertically (zenith absorption). For particles with ε_{k}= 1. 3-7 Mev, the inclination of the straight line is determined by the relation I = 2x10^{7} A$^{2.0}$ where I is the intensity of protons (m^{-2} sec^{-1} sterad^{-1}) and A is the magnitude of zenith absorption in decibles as measured by riometer at 30 MHz. This relation is in conformity with the expression I = 2x10^{5} A$^{2.0}$ obtained by Bailey [99] and the difference by a factor of ~10^{2} can be explained by the fact that protons with ε_k = 1.3-7 Mev interact in the atmosphere at altitudes higher than that of protons of higher energies and thus, play a smaller role in ionization and absorption of radiowaves. For ε_k > 33 Mev, the inclination of corresponding curves slightly differs from calculation results of Bailey [99].

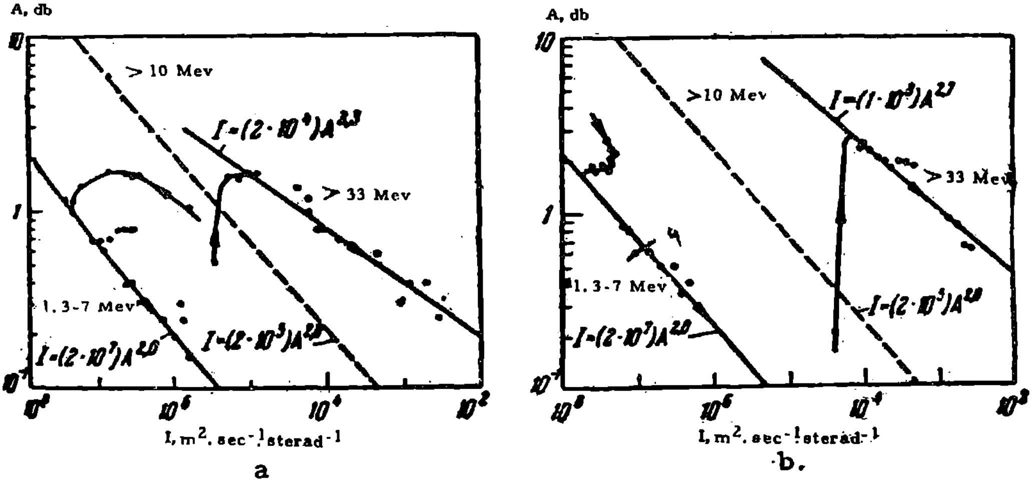


Fig. 10.4. Absorption amplitude from data of 30 MHz riometer at the South Pole as a function of the intensity of proton beam with ε_k = 1.3-7 Mev and ε_k > 33 Mev recorded by the satellite "Alouette" in September 1963.
a - September 21, 1963; b - September 26, 1963. Calculation results of Bailey [99] are shown by dotted lines; arrows show the time sequence of the points.

The amplitude of absorption of cosmic radio noise changes from day to night by about 4 times. But since the riometer, whose data was used for comparing with the satellite measurements, was installed at the south geographical pole and since the events of absorption described here took place in September, the ionosphere around the South Pole was for all the time illuminated by the Sun which helped in eliminating daily variations of absorption. The obtained empirical relations obviously depend upon the spectrum of solar particles but even then the curves of Fig. 10.4 can be used for determining the flux of solar protons in certain energy range from the data of riometers only.

The data of observations on the flux of protons generated during flares, which were obtained from the satellite "Alouette", are analyzed in detail by Burrows et al. [100]. Following are the results of the analysis:

1. The differential spectrum of protons from September 21, 1961 flare had the form $\sim \mathcal{E}_k^{-3.2}$ for protons with $\mathcal{E}_k$ = 33-400 Mev.

2. One hour after the September 21 flare, the flux of protons with $\mathcal{E}_k$=33-400 Mev increased by 4 times in the limited range of latitudes and longitudes. The interpretation of this increase as due to shock zone leads to the conclusion that the source extending to about 20° along the width was situated at 10° south of the Sun's equatorial plane and 75° east of the Earth-Sun line.

3. The low-latitude cut-off before the sudden commencement of magnetic storm for protons with $\mathcal{E}_k$ =114-165; 50-60; 33; 1.3-7 Mev took place at L = 4.1; 4.5; 4.5 and 5.3 respectively. The cut-off for protons with $\mathcal{E}$ = 1.3-7 Mev decreases to L=4.1 after the sudden commencement on September 21 and 27.

4. The values of the flux of protons decrease exponentially with the passage of time during magnetically quiet periods. Characteristic times of attenuation (5-8 hrs) are different for the two flares and for different energies but are considerably less than those observed in July 1961 (20-24 hrs). The flux of low-energy protons is more sensitive to disturbances in the interplanetary medium than the flux of high-energy protons.

5. Riometer readings at Resolute correspond better to component with $\mathcal{E}_k$= 1.3-7 Mev than to component with $\mathcal{E}_k > 33$ Mev.

In the period of high solar and geomagnetic activity during September 15-30, Harding et al. [101] measured solar cosmic rays on satellite "Injun-3" at geographical latitudes right up to 71°. Time variations of intensity, latitude effect and spectrum of solar protons with energy $\mathcal{E}_k > 0.5$ Mev were obtained.

Mention is made of the increase in the intensity of solar protons from February 5, 1965 flare in the work of Paulikas et al. [10]. This class 2 flare was observed at 1750 UT at a point with heliocoordinates 8°N, 24°W. Protons with $\mathcal{E} > 10$ Mev were measured with the help of satellite "1964-45-A" which had almost polar orbit (inclination ≈ 96°). The spectra and time variation of solar protons for February 5-8, 1965 were obtained.

The data given in [102] refer to altitudes of about 400 km over the southern and northern polar regions. The general nature of time variations of solar protons is shown in Fig. 10.5 for many threshold energies. The beginning of the optical flare, moment of arrival of protons with $\mathcal{E} > 10$ Mev (from the data of "Mariner-4" at a distance of 1.1 astronomical units from the Sun), sudden commencement of geomagnetic storm and time variation of K_p-index are also shown in this Fig. Due to technical reasons, data for the first few hours after the optical flare are absent.

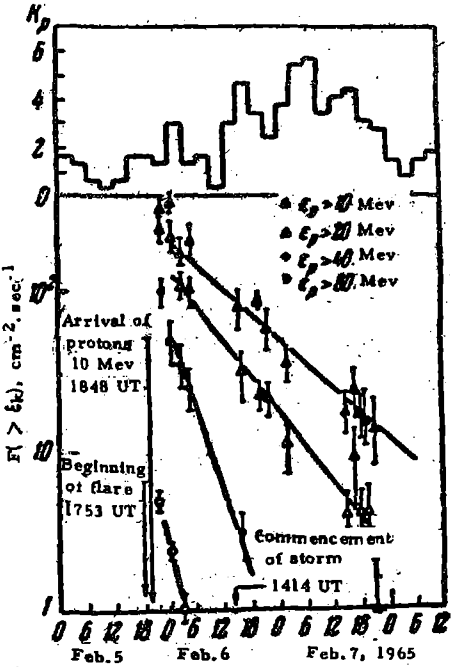


Fig. 10.5. Time variation of solar cosmic rays from February 5, 1965 flare [102].

It is interesting to mention that no dispersion in the velocity of protons was observed during the period under reference. Significant changes in the flux of protons were also not observed at the time of arrival of plasma cloud and subsequent geomagnetic storm to the Earth which started at 1414 UT on February 6, 1965. Obviously, the energy thresholds of detectors used in [102] were very high for recording low-energy particles which could arrive at the beginning of the geomagnetic storm. According to Parker [103], these particles could have been accelerated in the space between quiet solar wind and plasma cloud moving from the Sun and related to solar flare or could have been trapped in the region behind the front of plasma cloud. During the next revolution of the Sun, no increase in the intensity of solar protons was observed as compared to the galactic cosmic-ray background (≈ 3 particles.cm^{-2}. sec^{-1}).

The integral spectra of solar protons are given in Fig. 10.6 for three different times when short-lived fluctuations of intensity were not observed. Spectra obtained before and after short-lived sudden increase (fluctuations) of intensity of solar protons at 0020 UT on February 6, 1965 are also given in [102]. Paulikas et al. [102] consider that fluctuations in the flux could have been caused by changes in the direction of proton beam beyond the limits of the magnetosphere.

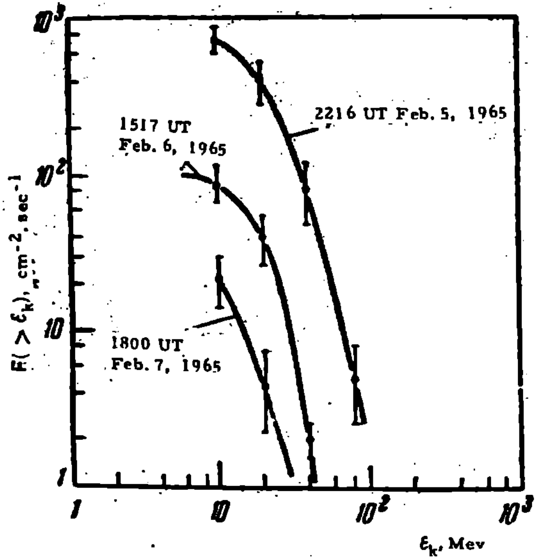


Fig. 10.6. Integral spectra of protons at different stages of the flare when time fluctuations were absent [102].

Table 10.2 gives a representation of time characteristics of the described phenomenon. As can be seen from Table 10.2, the characteristic attenuation time T_0 does not simply depend upon the average speed of protons, which may be expected from diffusion theory when the effective mean free path for diffusion does not depend on energy and $T_0 \sim 1/\bar{v}$ (see Section 14.3). The time variation of protons with ε_k = 10-35 Mev considerably differs from that of protons with $\varepsilon_k > 40$ Mev. It can be explained by assuming that the source has a complicated spectrum or that the propagation of particles differs from the simple diffusion process; moreover, the effective mean free path for diffusion possibly depends on the rigidity of particles.

TABLE 10.2

Decrease in the intensity of integral flux of protons on February 5, 1965 [102]

ε_k, Mev	T_0, hrs	$T_\sigma \frac{\bar{v}}{c}$, hrs	Integral flux four hours after the optical flare, cm^{-2} sec^{-1}
10	$16.8^{+2.7}_{-2.2}$	$3.7^{+1.2}_{-0.6}$	350
20	$11.6^{+2.1}_{-1.6}$	$3.0^{+0.9}_{-0.7}$	250
40	$4.7^{+1.3}_{-1.0}$	$1.5^{+0.6}_{-0.5}$	100
80	$4.0^{+0.3}_{-0.9}$	$1.7^{+0.2}_{-0.5}$	5

The flare of February 5, 1965 was also recorded by "IMP-2" and "Mariner-4" (Van Allen and Krimigis [104], O'Gallagher and Simpson [127]) but the values of T_0 obtained were 800 min. and 1100 min respectively for the integral flux of protons with $\varepsilon_k > 15$ Mev. The time variation of such protons, is shown in Fig. 10.7.

The equipment installed on "Mariner-4" included three face Geiger counters two of which had threshold energies for electrons ~ 40 kev and the third one, ~ 15 kev (these counters were capable of recording protons with $\varepsilon \geqslant 55$ Mev) and one semiconductor proton detector which was not sensitive to electrons (level of discrimination $0.50 \leqslant \varepsilon_p \leqslant 11$ Mev and $0.88 \leqslant \varepsilon_p \leqslant$

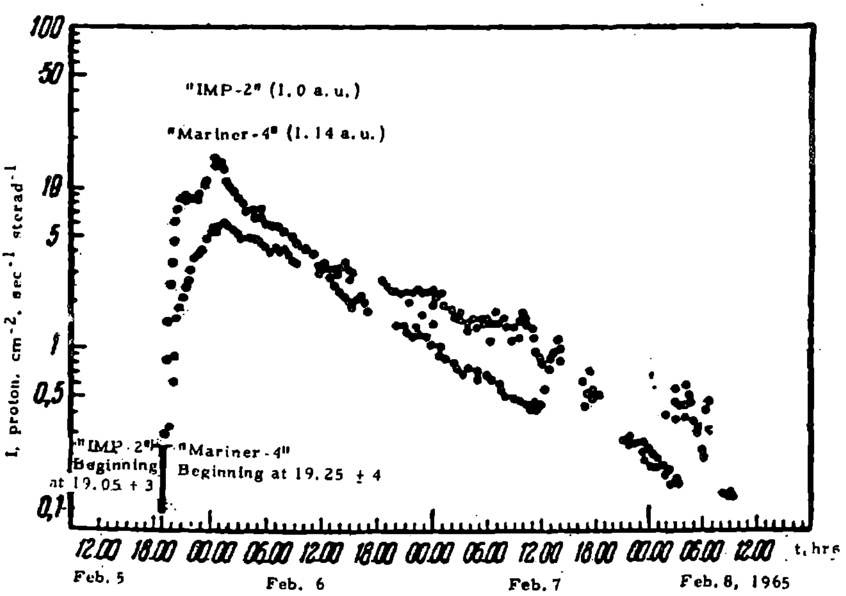


Fig. 10. 7. Time variation of solar protons with $\mathcal{E}_k$ >15 Mev for February 5, 1965 flare from the data of "IMP-2" and "Marines-4".

4 Mev). During February 5-13, "Mariner-4" was situated at a distance of 1.14 astronomical unit from the Sun. The angle between the Earth-Sun and Earth-"Mariner-4" directions was equal to 1.9°. An outburst of corpuscles was recorded at 1840±0010 UT on February 5, 1965. Protons as well as electrons with $\mathcal{E} \sim 40$ kev and having very steep spectrum were observed (see Section 22). The fluxes at the maxima (2130 UT) were F_e ($\mathcal{E}_p \geqslant$ 55 Mev) ~ 80 cm^{-2}. sec^{-1} and F ($\mathcal{E} \gtrsim$ 40 kev) ~ 700 cm^{-2}. sec^{-1}. The low-energy protons ($0.50 \leqslant \mathcal{E}_p \leqslant 11$ Mev) showed complicated change of intensity with time. Many maxima were observed during 8 days, the biggest being at 0900 UT on February 7, 1965 and I_{max} = 125 cm^{-2}. sec^{-1}. sterad^{-1}. The propagation of protons with $\mathcal{E} \gtrsim$ 55 Mev is in conformity with the diffusion model in which the diffusion coefficient increases with distance as $r^{2/3}$. However, at low energies, the propagation does not conform to any simple diffusion model.

From October 17, 1963 to October 1965, Felthauser et al. [105] made minute observations on solar and galactic cosmic rays with the help of neutron and scintillation detectors (threshold energy ~ 20 Mev) aboard the satellites "Vela". The satellite orbits were close to circular one with radius 16-20 r_E.

The integral intensity of cosmic rays of energy higher than the threshold energy was recorded continuously. The most powerful of all the recorded solar flares took place on February 5, 1965. The intensity of the October 4, 1965 flare was about 10% of the intensity of February 5, 1965 flare on the assumption that the energy spectra are similar. The upper limit of the flux of solar protons with $\mathcal{E} > 0.5$ Mev was determined with the help of a Geiger counter having a thin window.

In the middle of April 1965, Houston and Earhart [106], on the basis of riometer data at 22 MHz at Durkhem, recorded unusual variations in the flux of cosmic rays which were accompanied by large fluctuations in the horizontal component of the geomagnetic field.

Heristchi et al. [107] recoreded the increase in the flux of protons with $\mathcal{E}_k \gg 100$ Mev on July 7, 1966 in stratosphere over North Scandinavia. Time variation of these protons, change in the index of their differential spectrum with time and 27.6 MHz riometer data at Kiruna (Sweden) are shown in Fig. 10.8. Neutron monitor at Kergelen Island (sea level, cut-off rigidity 1.28 Gv) also recorded a small ($\sim 2\%$) increase in the intensity*.

It is interesting to mention that a clear sudden decrease in the intensity of proton beam with $\mathcal{E}_p \sim 0.5$ Mev was observed on the satellite "Explorer-33" at 2106 UT on July 8, 1966 in the interplanetary space at a distance of 187,000 km from the Earth. Obviously, solar flare observed at 0027 UT on July 7, 1966 emitted the protons. Sudden decrease in the intensity conforms to the effect of interplanetary shock wave whose detailed structure was observed with the help of the triple-component ferroprobe magnetometer installed on the satellite.

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* *Pomerantz et al. [167] also recorded the increase in the intensity of cosmic rays at sea level on July 7, 1966. This was the first result obtained with the help of network of supermonitors installed at high latitudes in both the hemispheres. The effect of amplitude ~1% was observed at those stations where the geomagnetic cut-off was less than that caused by the atmosphere. The increase was not observed at Svartmore where geomagnetic threshold is 1.92 Gv. The July 7, 1966 flare was also recorded by Lin et al. [171] with the aid of the satellite 'IMP-1" ('Explorer-33'). Comparison with simultaneous observations on the satellites 'IMP-3" and 'OGO-3" facilitated detection of a number of unusual characteristics of this complicated phenomenon.*

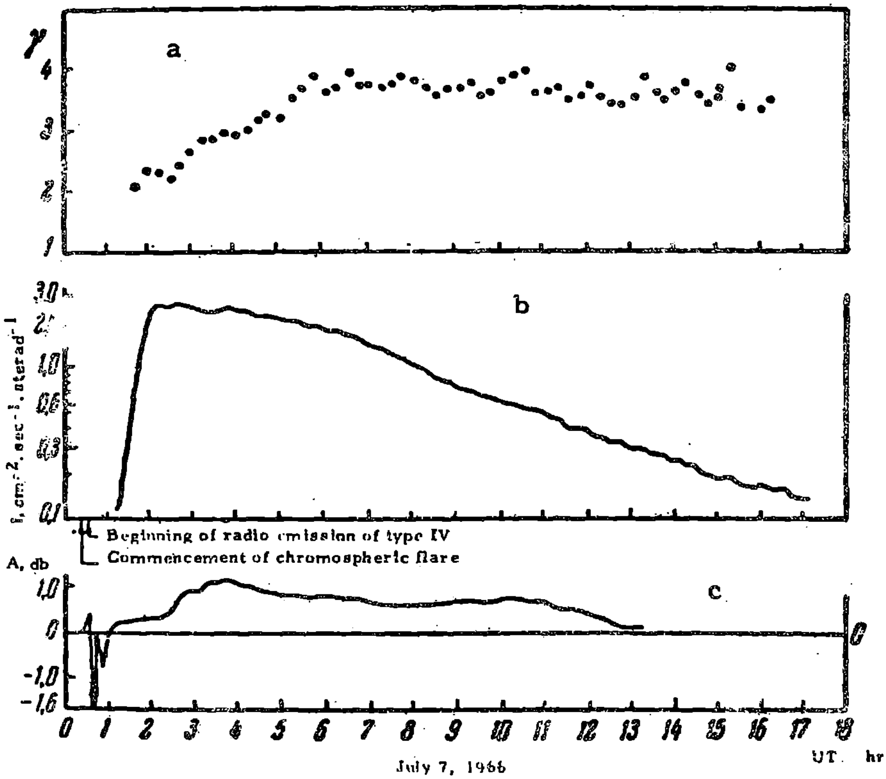

Fig. 1C.8. Change, with time, in the index of differential spectrum of protons with $\mathcal{E}_k$ = 100-500 Mev (a), intensity (b) and absorption amplitude of cosmic radio noise (c) during July 7, 1966 flare.

A number of solar proton flares were also recorded in August-September 1966 and in January and May 1967. The increase in the intensity of cosmic rays, observed by the world network of stations on January 28, 1967, is of great interest (see Section 14).

According to Blake et al. [172], the propagation of solar protons from class 3 flare, observed at 1530 UT on August 28, 1966, was recorded by the equipment aboard the satellite "1966-70A" [110]. At 2000 UT on July 29, 1966, the intensity of protons with $\mathcal{E}_k$ = 2 Mev at high latitudes was 2.5x10^3 cm^{-2}, sec^{-1}, sterad^{-1}, Mev^{-1}; at 1820 UT on August 30, it attained a value of 7.5x10^{-3} while the flux of protons with $\mathcal{E}_k$ = 8 Mev during this period reduced.

With the help of 2-100 Mev proton detector installed on the satellite "OGO-3", Kahler et al. [128] measured the flux and anisotropy of these protons during August 28, 1966 flare and magnetic storm connected with this flare (sudden commencement at 1314 UT on August 29, 1966). A few Mev proton flux after sudden commencement increased to $2x10^3$ cm^{-2}. sec^{-1} while the anisotropy was 4:1 and did not depend on energy. Comparison of the measuremed data and Roelof's model of propagation of particles [IV. 23] shows that scattering at magnetic irregularities is not so large that distribution according to pitch-angles may approximate to an asymptote.

On the basis of data obtained with the aid of the Moon satellites "Luna-11" and "Luna-12", N. L. Grigorov et al. [164] studied time variations of protons with $\mathcal{E}_k > 50$ Mev and $\mathcal{E}_k > 1.8$ Mev during the period August 28-October 1, 1966 and October 25, 1966-January 5, 1967. Sudden increases in the flux of protons were observed after solar flares of August 28 and September 2, 1966. Simultaneous measurements of protons with $\mathcal{E}_k > 400$ Mev were conducted on "Proton-3" while no increase in the intensity of cosmic rays was observed within the limits of ± 10%. The integral spectrum $I(>\mathcal{E}) \sim \mathcal{E}^{-\gamma}$, where $\gamma > 1$ and $\gamma > 1.7$ for August 28 and September 2 flares respectively, was determined by taking into account these results. The intensity of protons decreased on September 2 according to the law $\sim t^{-3.4}$ (time is counted from the moment of optical flare). According to Masley and Goedeke*, the outburst of September 2, 1966 was the most powerful one after July 18, 1961. According to data of N. L. Grigorov et al. [164], the flux of protons with $\mathcal{E}_k > 50$ Mev on September 2, 1966 was 400 cm^{-2}. sec^{-1} (by 2 orders more than the galactic background $\sim$ 4 cm^{-1}. sec^{-1}). The intensity of protons with $\mathcal{E}_k > 1.8$ Mev underwent strong flunctuations.

Mention is made in the work of P. N. Ageshina et al. [109] of the measurements on solar protons over Murmansk and Mirny (Antarctica) during the flares on July 7, 1966, September 2, 1966 and January 28, 1967. The intensity of protons on July 7 over Mirny at a pressure of 8 g/cm^2 was 0.7 cm^{-2}. sec^{-1}. $sterad^{-1}$ which is close to the intensity of about 0.8 cm^{-2}. sec^{-1}.

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* *Report read at the International Conference on Cosmic rays, Canada, July 1967.*

$sterad^{-1}$ over Kiruna observed by Heristchi et al. [107] at the same pressure. The integral spectrum of protons over Mirny had the form $\varepsilon_k^{-2.6}$ which is also in conformity with the results [107]. Equality of fluxes and coincidence of spectra of solar protons at Kiruna and Mirny point out the isotrpy of particles in the terrestrial space.

For the September 2, 1966 flare, integral spectrum of protons had the form $\varepsilon_k^{-3.7}$ and practically did not change during the whole of the phenomenon.

During January 28, 1967 flare, the maximum intensity of protons at a height with pressure 8 g/cm^2 over Murmansk was 1.8×10^6 m^{-2}, sec^{-1}, $sterad^{-1}$. During simultaneous measurements at Murmansk and Mirny, the intensity of protons in stratosphere coincided which points out the isotropy of particles near the Earth. The index of integral energy spectrum in January 28, 1967 measurements in the range ε = 300-600 Mev was $\gamma = 3.5$ while in January 29-30 and February 1, 1967 measurements, $\gamma \approx 3.0$ in the energy range of 80-400 Mev. In magnitude, this flare was close to November 15, 1960 flare.

Time variation of the intensity of protons for July 7, 1966 and January 28, 1967 flares well conforms to diffusion curves on the assumption that the generation on the Sun lasts for a relatively short period and $\varkappa = \varkappa_{\delta}(\lambda/r_{\delta})$ where $\beta \approx 1$. The increase in the intensity during September 2, 1966 flare was slower than the decrease and thus, it is not possible to describe the time variation by a usual diffusion curve. By comparing the data of neutron monitor at Chicago with the results of stratospheric measurements of January 28, 1967 over Murmansk, it is shown in [109] that Λ = const = 7.4×10^{11} cm for nonrelativistic protons.

The value $\Lambda = 1.4 \times 10^{12}$ cm for July 7, 1966 flare was higher than that for September 28, 1961 flare. In both the cases, solar activity was the same (total number of groups of solar spots during the month $\eta = 120$). A similar effect at $\eta = 230$ was observed during the flare events of January 28, 1967; April 1, 1960 and May 4, 1960 for which values $\Lambda = 7.4 \times 10^{11}$ cm, 7.1×10^{11} cm and 9.8×10^{11} cm were obtained respectively.

During the flare of September 2, 1966, protons were also recorded by Paulikas et al. [110] and Gram [168] on the satellite "1966-70-A" having polar orbit. A counter telescope to measure the spectrum of protons in eight energy intervals in the range of 23-300 Mev was installed on the satellite. Another telescope (of semiconductor detectors) and 4 nondirectional detectors covered the energy ranges of 1.1-18 Mev (4 intervals) and 12-130 Mev respectively. According to Gram [168] and Paulikas et al. [110], the intensity of protons with energy of 29 Mev during September 2, 1966 flare remained constant for 15 hours while for energy ~ 55 Mev during the same period, it changed from 7 to 1 cm^{-2}, sec^{-1}, sterad^{-1}, Mev^{-1}. The intensity of protons with energy of 100 Mev was < 0.1 cm^{-2}, sec^{-1}, sterad^{-1}, Mev^{-1} and the differential spectrum had the form $\sim \varepsilon_k^{-4}$. Fluxes of 470 and 17 cm^{-2}, sec^{-1}, Mev^{-1} were observed for protons with energies of 20 and 100 Mev respectively in the northern polar cap at 1945 UT on September 2, 1966. The time constant of energy attenuation at these energies was 19.6 and 3.4 hours respectively.

Much information on solar protons from September 2, 1966 flare was obtained by Zmuda et al. [169] with the help of the satellite "1963-38C". During September 2, 1966 flare, Brown and Parthasarathy [170] observed absorption of cosmic radio noise in the Earth's polar regions.

10.5 Transport of solar particles in magnetic traps of corpuscular beams. In May 1959, A.N. Charakhch'yan et al. [I. 13] and Ney et al. [I. 12] independently recorded a large increase (by ~ 40 times) in the flux of protons with $\varepsilon_k \geq 120$ Mev with the help of cosmic-radiation detectors flown on balloons. The beginning of the effect was found to be coinciding with the commencement of a magnetic storm. An analysis of these data, done by L.I. Dorman [111], showed that in the front part of the corpuscular beam, there was a magnetic trap having specific properties. The characteristic feature of this increase is the exponential form of the subsequent decrease in intensity $e^{-t/2}$ (t in hours) which very much differs from the usual diffusion law.

Analyzing the two-fold nature of the November 12, 1960 increase, Kodama and Kitamura [112] arrived at the conclusion that the second increase was apparently caused by particles captured in the magnetic trap of the corpuscular beam since the analysis of solar data during this period certifies to the absence of emission of cosmic rays by the Sun. An approximate explanation of this effect is given in the work of Steljes et al. [113].

About two days after the September 28, 1961 solar flare, a magnetic storm with sudden commencement was observed on the Earth. During the storm, the decrease in the intensity of galactic cosmic rays as observed by Bryant et al. [I. 23] from the data of "Explorer-12" was 1.7 ± 0.3 times the decrease from the data of neutron monitor at Deep River. At the same time, the flux of solar protons with $\mathcal{E}_k < 15$ Mev increased considerably (by tens of times). Bryant et al. [I. 23] assumed that these low-energy protons were transported to magnetic trap of the corpuscular beam which had caused the magnetic storm and Forbush effect. It should be mentioned that the increase is studied right up to $\mathcal{E}_k \leqslant 200$ Mev. It shows the upper limit of the energy of particles captured in the magnetic traps. Measurements of Hofmann et al. [114] on the same satellite for a beam of protons with $\mathcal{E}_k = 0.1$-5 Mev as well as the data of Van Allen and Whelpley [IV. 70], obtained with the help of the satellite "Injun-1" during the same period, do not contradict the conclusion of Bryant et al. [I. 23]*

Essentially, these are the examples when it was possible to interpret the time variation of the intensity of solar cosmic rays on the basis of the concept of magnetic traps of corpuscular beams. Thus, although the transfer of low-energy solar cosmic rays to magnetic traps is apparently one of the usual methods of transportation of particles from the Sun to the Earth, this process is more rare than propagation by diffusion.

Closed-configuration regular magnetic field can, in principle, serve as an ideal trap. However, the effectiveness of even the ideal trap will, obviously, significantly depend on the energy of particles: one and the same magnetic formation can become an opaque trap for particles of energy less than some critical value and can be practically transparent for particles having higher energy. Should only the formations with regular magnetic fields of special configuration, in which life of charged particles is very large and the effect of accumulation of particles is significant, be considered as the cosmic magnetic trap or should a wider sense be imparted to this concept?

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* *As shown by Parker [103], the attempt to explain the observed effects of the increase in the beginning of a geomagnetic storm by acceleration of particles on the Sun has run into many difficulties. B.A. Tverskoi [V.182] assumes that these effects are cases of most intensive turbulent acceleration in the interplanetary medium (see remark on p 458).*

From the point of view of the study of general laws of cosmic-ray intensity variations, it is advisable to consider all magnetic formations, in which movement and duration of existence of charged particles considerably differ from those in free space of the same volume, as cosmic magnetic traps. This approach facilitates unique consideration and explanation of many types of variations of cosmic rays including flares of solar cosmic rays similar to those observed on May 11-12, 1959.

10. 6 Classification of increases in the intensity of cosmic rays. According to the data systematized in [I. 1, I. 2], the increases observed on the Earth can be classified in the following way depending upon the nature of propagation of solar particles in the interplanetary space (see L. I. Dorman [I. 2], McCracken and Palmeira [115]).

Increase of type A follows immediately after a class 3 or 3^+ chromospheric flare and contains direct and scattered components of solar radiation. The intensity of cosmic rays on the Earth attains the maximum value very quickly and subsequently starts decreasing gradually according to the law $\sim t^{-3/2}$ or $\sim t^{-2}$. The beam of solar particles is extremely anisotropic at the initial stage. The intensity of this direct radiation decreases (in contrast to the scattered radiation) exponentially which is related to diffusion of particles from the solar supercorona. In this case, the path from the Sun to the Earth is free from scattered magnetized clouds (Fig. 10. 9, a). Such events were observed, for example, in March 1942, November 1949, February 1956 and May 1960. All chromospheric flares, causing these increases, were observed on the western edge of the solar disk.

Increase of type B follows with some delay after the chromospheric flare and contains only the scattered part of solar

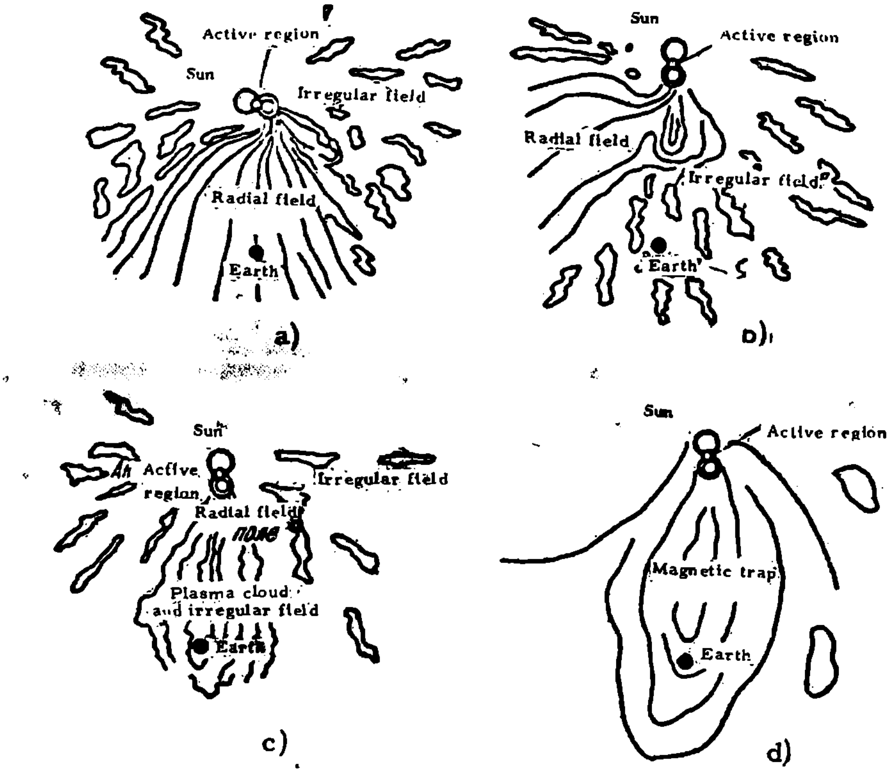

Fig. 10. 9. Propagation of solar cosmic rays: a), b), c) in the absence of a magnetic trap; d) in the presence of a trap in corpuscular beam.

radiation. The intensity increases gradually, has extremely diffused maxima and afterwards, starts decreasing according to the same law as the increase of type A. In this case, there are scattering, magnetized clouds (Fig. 10. 9, b) on the path from the Sun to the Earth. This type of increases were observed in February 1942 and in July 1946 (the corresponding chromospheric flares were observed near the central meridian).

Increase of type C has significant time lag with respect to the chromospheric flare and lasts for a long time. It takes place during Forbush effect when the Earth is surrounded by solar corpuscular beam related to an earlier chromospheric flare (Fig. 10. 9, c). Such a case was observed, for example, in July 1959.

Increase of type D in the beginning resembles to the increase of type C. Subsequently, after the commencement of magnetic storm, a sudden increase in the intensity and quick exponential decrease are observed. Afterwards, the decrease continues according to the law $t^{-3/2}$ or t^{-2}. Such an increase was observed in May 1959 and in many other cases (see Section 10.5) when there was apparently a magnetic trap of solar particles in the corpuscular beam (Fig. 10.9, d).

In the end of this Section, let us study the data on the dependence of amplitude of the increase on time for some of the very strong flares. These data are given in Fig. 10.10 in the logarithmic scale and the time is counted from the beginning of the chromospheric flare. Time dependence of scattered flux of solar particles is shown for the well-known five large increases. In order to plot Fig. 10.10, the data of high-latitude station Godheaven were used at which intensity of cosmic rays was recorded continuously for a few decades with the help of a shielded ionization chamber. If the simultaneous measurements made in stratosphere during February 23, 1956 flare [I.9, I.11) are used, the data can be recalculated to the conditions of stratosphere for comparison purposes. The conversion factor for this flare was found to be about 300. The data on the remaining four flares were recalculated with the help of this coefficient. Of course, it is a very crude conversion assuming the consistency of spectrum during all the flares. Therefore, much importance should not be given to the absolute height of the obtained curves; only the relative change in the intensity with time is significant. Theoretical curves of time variation for particles with diffusion coefficients of 10^{21} and 10^{22} cm^2/sec are shown in Fig. 10.10 by full lines for the sake of comparison. It may be seen that the change in the intensity for different flares is more or less similar. The flare events of May and July 1959 are apparently exceptions which are studied below separately.

As mentioned in Chapter 1, a significant increase in the intensity of solar particles with $\mathcal{E}_k \approx 110\text{-}220$ Mev was observed by Ney et al. [I.12] and A.N. Charakhch'yan et al. [I.13] on May 11-12, 1959. The analysis of the data, made by Ney et al. [I.12], showed that, at an altitude with pressure 19 g/cm^2, the additional flux mainly consisted of protons which, in any case, did not come from the internal zone of the radiation. Moreover, there were no α-particles and heavy nuclei in the beam. The differential spectrum of solar protons in the energy range 110

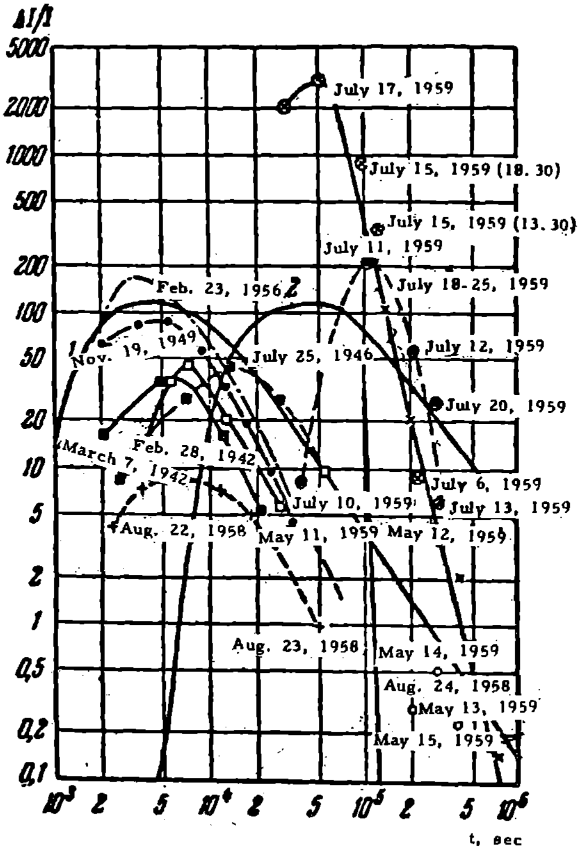

Fig. 10.10. Nature of change with time in the intensity of solar particles for a number of solar flares. Curves 1, 2 - theoretical curves for $\varkappa = 10^{22}$ and 10^{21} cm^2/sec respectively, t - time after the beginning of solar flare.

Mev $< \varepsilon_k <$ 220 Mev can be represented in the form $\sim \varepsilon^{-4.8}$. The magnetic storm caused a significant decrease in the intensity of cosmic rays at sea level which is similar to the Forbush effect. During this period, a large increase in the intensity of low-energy particles was observed in stratosphere whose amplitude decreased along the exponent by 10 times during 4 hours (Fig. 10.11). During this period, the cut-off rigidity for Minneapolis reduced considerably which is related to the disturbance in geomagnetic field by plasma cloud caused by the magnetic storm.

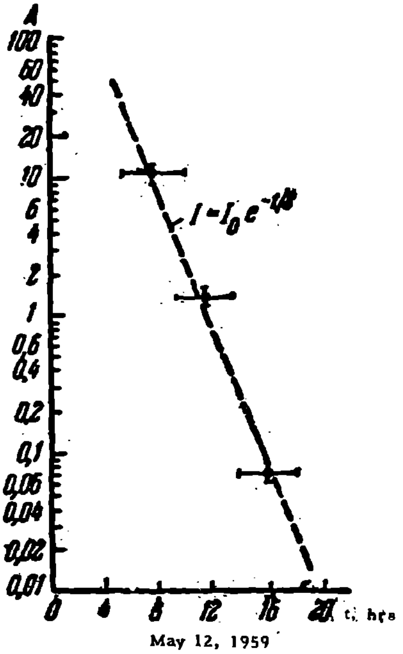

Fig. 10.11. Decrease in the amplitude of increase in the intensity of solar particles with time in May 1959 [112].

If the normal concentration of cosmic rays is taken to be 10^{-10} cm^{-3}, theoretical curves shown in Fig. 10.10 correspond to 10^{32} particles, emitted by the Sun. A comparison with the experimental curves on the known five flares as well as on August 1958 flare shows that the value $\varkappa \sim 10^{22}$ cm^2/sec, i.e., $\Lambda \sim (1\text{-}3) \times 10^{12}$ cm is possible quite often, although there are deviations in both the directions (for example, for July 25, 1946 flare, $\varkappa \sim 3 \times 10^{21}$ cm^2/sec).

Considerably lesser values of $\varkappa$ should be expected for July 1959 flares when the maximum increase took place much later than the above-mentioned five flares observed at sea level. This may be related to the decrease in Λ as a result of the forces of solar activity and appearance of corpuscular beams with regular magnetic field but with scattering magnetic irregularities which facilitates even the low-energy particles to drift in the beam.

The decrease in the intensity observed in July 1959 was even faster than the decrease during other periods. This conclusion was drawn by Anderson and Enemark [116] who on balloons above "Resolute" observed strong flux of low-energy solar protons connected with July 16 flare at 2115 UT. Blackout in radiocommunications at short waves and absorption of cosmic radio noise was noticed at high latitudes at 2300 UT which pointed out to the invasion of low-energy protons in the D-layer of the ionosphere. A beam of protons with ε_k = 85-300 Mev, whose intensity was much higher than that of galactic background, was recorded at altitudes with pressure 6 g/cm^2, 25 hours after the beginning of chromospheric flare. The spectrum of protons during this period had the form $\sim \varepsilon_k^{-6.1}$. During subsequent days, the intensity of particles decreased quickly although some additional flux of radiation was still present on July 27. Time dependence of decrease in the intensity of protons well conforms to the power law t^{-3} where t (measured in hours) is counted from the moment 16 hours after the flare.

Quicker decrease in the intensity as compared to the law $\sim t^{-3/2}$ might be caused by two reasons: 1) the mean free path for scattering increases with an increase in the distance from the Sun (see Section 14.6); 2) there is additional drift of solar particles in the direction from the Sun due to directional and radial movement of magnetic irregularities in corpuscular beam (see Section 14.9).

11. SOLAR COSMIC RAYS AND BACKGROUND OF LOW-ENERGY PARTICLES IN THE INTERPLANETARY SPACE

11.1 Experimental data on low-energy solar protons. The generation of solar cosmic rays is usually related to discrete events on the Sun, starting during flares in the active regions and accompanied by radio-flares of type IV on wavelengths ranging from a few centimeters to tens of meters. It is assumed that the acceleration of particles in this case continues for a period of the order of a few minutes while the flare lasts for 0.5-2 hrs. Low-energy protons having energy of a few kev, which are related to widening of the corona and which form the plasma of solar wind, constitute another type of emission of solar particles.

Investigations conducted during previous years led to another component -- protons with $\mathcal{E}_k = 0.5$-10 Mev. Measurements on the intensity of these protons in the interplanetary space facilitate the study of long-life solar corpuscular beams and fine structure of the interplanetary magnetic field.

In 1961, Bryant et al. [117] recorded two cases of increasee in the intensity of solar protons with $\mathcal{E}_k > 3$ Mev (October 27 and December 1, 1961) with the help of the satellite "Explorer-12". These increases were not connected with solar flares but coincided with the commencement of magnetic storm and Forbush decrease, at that moment when the central meridian intersected the active region responsible for the flare and increase in solar cosmic rays during the previous revolution of the Sun. The amplitude of the increases on October 27 and Decmber 1, was very small and as such, they probably could not be recorded by riometers.

Recent direct measurements by Snyder and Neugebauer [118] on "Mariner-2" in the interplanetary space testify to the 27-day structure of the interplanetary plasma. There was no special equipment on "Explorer-12" for measuring the plasma but increases in the intensity of protons with $\mathcal{E}_k > 3$ Mev indicate that fluxes of plasma and magnetic fields can drag the protons out of the solar surrounding, can accelerate them locally or can capture the particles remaining from the previous flare of solar cosmic rays.

Fig. 11.1 shows the intensity of protons with $\mathcal{E}_k > 3$ Mev beyond magnetosphere from the subsolar side during the period September 30 -- October 28, 1961. A class 3^+ flare of September 28, 1961 caused a large increase in the flux of comparatively high-energy solar protons. After two days when the intensity of particles had already been maximum, an increase in the flux of protons with $\mathcal{E}_k > 3$ Mev was recorded which was 10 times the maximum intensity of September 28, 1961 increase. A magnetic storm with sudden commencement and Forbush effect, recorded by "Explorer-12" and ground neutron monitors, was observed simultaneously. The increase in the intensity of protons and geophysical disturbances were finished on October 7, 1961. A new increase was observed on October 27, 1961 along with geomagnetic storms and Forbush effect. This increase is not similar to the flare of cosmic rays, it was not preceded by solar disturbance and the event lasted for only a few hours. Moreover, the time of arrival of particles did not depend on their velocity, i.e., form of the spectrum during the event practically did not change, while index in the range $\mathcal{E}_k$ = 3-10 Mev was within the limits of 4-5. Bryant et al. [117] consider that the October 27, 1961 increase is related to the long-life corpuscular beam from September 28, 1961 flare.

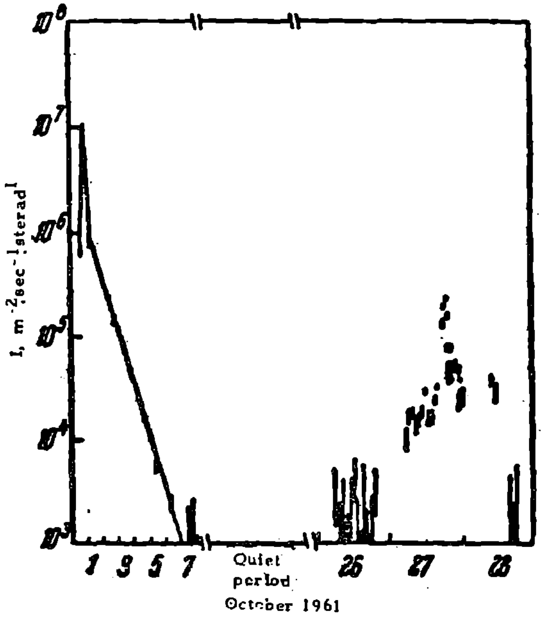

Fig. 11.1. Intensity of protons with $\mathcal{E}_k \sim 3$ Mev during September 30 - October 28, 1961 from the data of 'Explorer-12" [117].

A similar event was recorded on December 1, 1961, three weeks after November 10, 1961 solar flare which had occurred at the western limb of the Sun and was followed by radio emission of type IV and outburst of solar protons [1.23]. The increase of December 1 was accompanied by a magnetic storm and Forbush effect. This event coincided with the passage, across the central meridian, of an active region where November 10, 1961 flare had taken place. Thus, the existence of long-life flux of plasma is once again confirmed and the time differences can be explained by the difference in the location of corresponding solar flares.

The increase of September 18, mentioned in the work of Bryant et al. [117] has apparently the same nature as, the December 27, and 1, 1961, events.

In another work of Bryant et al. [119], proof is given of the prolonged existence of protons with $\mathcal{E}_k$ = 3-20 Mev in the interplanetary space. The lower limit of about 3 Mev corresponds to the threshold of the detector used. Hence, it can be expected that the spectrum of this new component is diffused in the region of much lower energies. As mentioned by McDonald and Desai [120], the increases in the flux of low-energy protons were recorded by "Explorer-14" in 1963 during seven consecutive revolutions of the Sun and the width of the beams changed within the limits of 30-120°. These seven events could be identified with the long-life series of M-regions or geomagnetic storms which started in August 1962, repeated every 27 days, and continued during the whole of 1964. Following are the characteristic features of these events : 1) very low intensity (about 1-5 cm^{-2} sec^{-1} $sterad^{-1}$ for $\mathcal{E}_k > 3$ Mev); 2) energy spectrum of the form $\sim \exp(-\mathcal{E}_k/\mathcal{E}_*)$ where $\mathcal{E}_k$ is the kinetic energy of protons and $\mathcal{E}_* \approx 2$ Mev at $\mathcal{E}_k$ = 3-20 Mev; 3) absence of a direct relation with solar flares or radio emission of type IV; 4) quasiequilibrium state confirmed by the absence of dispersion of velocities during propagation of particles and by the absence of anisotropy in the direction of propagation of particles; 5) 27-day cycle ; 6) rigid relation with geomagnetic disturbances; 7) sharp difference in the nature of increase and decrease in the intensity from that observed for increases due to solar flares.

With the aid of satellites "IMP-1" ("Explorer-18"), Bryant et al. [119] recorded a number of other recurrent events. At least in 3 cases during the end of 1963 and beginning of 1964, low-energy protons, observed on "IMP-1", came from the same regions of the Sun as during the observations on "Explorer-14". Fig. 11.2 shows the spectra at the time of maximum increase for a number of events during the first half of 1963. In general, parameter $\mathcal{E}_*$ changes to a lesser extent during one event. At such low energies, exponential spectrum from kinetic energy is equivalent to the power spectrum of total energy in Mev and $\gamma = 250$. Data at higher energies ($\mathcal{E}_k > 80$ Mev) for May 2, 1963 event with intensity of 0.1 proton. cm^{-2} sec^{-1} $sterad^{-1}$ cannot be attributed to any of the above-mentioned expressions.

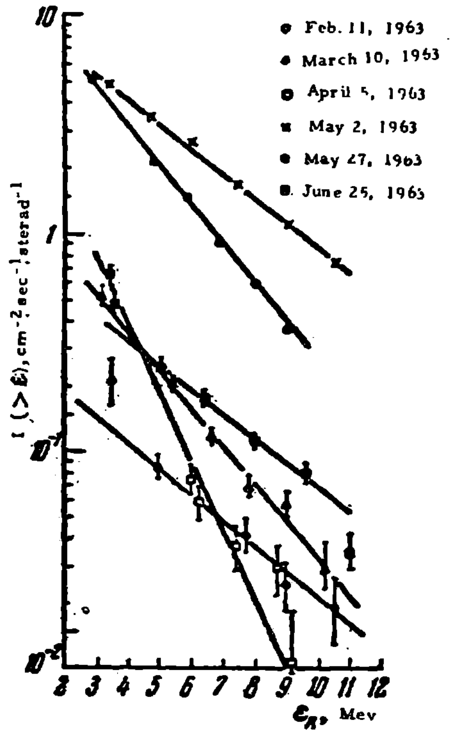

Fig. 11.2. Integral energy spectra of increases in the intensity of protons during the first half of 1963. Data is given for those events when maximum intensity was observed for protons with $\mathcal{E}_k > 6$ *Mev [119].*

Up to this time, the question is not clear as to where low-energy protons are accelerated - - near the surface of the Sun or in the interplanetary space (in the turbulent region between the fast-moving plasma of corpuscular beam and the surrounding slow-moving solar wind). Bryant et al. [119] prefer the latter of the two possibilities and consider that the data obtained by them confirm this point of view.

Acceleration in the turbulent region may be similar to the mechanism suggested by Parker [103] for the case of shock wave spreading in the interplanetary space. However, effective capture of low-energy solar particles appears to be less probable to the authors [119] because these particles can very freely propagate from the Sun to the Earth.

Solar corpuscular beams, consisting of low-energy protons, were studied by Sinno [122] and Mori et al. [123] as the source of geomagnetic disturbances from M-regions of the Sun during August 1962 and end of 1964. Plasma, related to such a beam, was observed in the cosmic space by Snyder [124] in September-December 1962.

Some large outbursts, described here, were also recorded by Van Allen and Whelpley [IV.70] (on "Injun-1") and Masley et al. [II.21] (from the data of polar riometers). However, observations on "Explorer-14" for the first time made it possible to undertake a systematic study of increase of low-energy solar protons with sufficiently sensitive equipment in order to get their energy spectra and to prove the recurrent nature of these events.

Identification of long-life active regions on the Sun, responsible for M-disturbances, was doubted upon for a long time. Two recurrent events, recorded by "Explorer-12" in 1961, finally showed that the corpuscular beams and geomagnetic M-disturbances are observed about a day after the passage of active region through the central meridian.

During the flight of "Mariner-4" to the Mars and afterwards (November 28, 1964 - October 1, 1965), Krimigis et al. [125] recorded protons with $\mathcal{E}_k \sim 500$ kev; moreover, interplanetary magnetic fields were measured simultaneously. A short resume of the obtained results is given below :

1. Starting from 1803rd revolution of the Sun, magnetic field during the period $\gtrsim 6$ days was opposite in direction as compared to the component corresponding to the ideal Archimedean spiral and the picture repeated every 27 days.

2. Every change in the direction of the field was accompanied by the immediate appearance of protons with $\mathcal{E}_k \gtrsim 0.5$ Mev. Their intensity during 1803rd revolution was ~ 0.8 cm^{-2}. sec^{-1}. sterad^{-1}; during 1807th revolution, the intensity attained the maximum value of ~ 6 cm^{-2}. sec^{-1}. sterad^{-1} and later on, decreased to 0.3 cm^{-2}. sec^{-1}. sterad^{-1} in 1808th revolution -- the last revolution during which measurements were taken.

3. The time profile of proton intensity has a structure with many peaks in the spectrum and the intensity can attain the initial value before the field comes to its original direction.

4. The intensity of field has a characteristic increase of about 3 γ in the beginning of every spectrum with a time lag about 1 day and afterwards, as the particles disappear, the field attains the normal value and once again, shows an increase of the same amplitude.

5. Only in one case, there is a definite relation between this type of event and sudden commencement of the geomagnetic storm.

It may be mentioned that some small proton flares are not related to variable sign of the field and they do not have 27-day periodicity.

Observational data of protons with kinetic energies $\mathcal{E}_{p1} = 0.5$-11 Mev and $\mathcal{E}_{p2} = 0.88$-4 Mev during the 10 months of the flight of "Mariner-4" in the interplanetary medium are discussed in detail in the work of Krimigis and Van Allen [126]. During this period, 20 events of appearance of solar cosmic rays were noticed whose intensity was more than 0.12 $cm^{-2}.sec^{-1}.sterad^{-1}$ (threshold sensitivity of detectors). A clear anticorrelation between the frequency of appearance of solar protons and the intensity of galactic cosmic rays is mentioned. During February 5-13, 1965, 20 events of strong flares of cosmic rays were observed but only one of them could be identified with chromospheric flare. The energy spectrum of protons in this case was very plane and the time variation of intensity of particles with $\mathcal{E}_p > 55$ Mev, measured by Geiger counter, is well described by the assumption of free diffusion in the interplanetary medium. In the remaining 19 events, change in intensity with time has asymmetrical profile and lasts from one to a few days. The ratio of intensities, measured by the two detectors remained almost the same during the period which is in agreement with the differential energy spectrum of the type $dI/d\mathcal{E}_k = \exp(\mathcal{E}_k/\mathcal{E}_*)$ where $\mathcal{E}_* = 200$-600 kev or $dI/d\mathcal{E}_k \approx k^{-\gamma}$ where $\gamma = 2$-4. In five cases, the appearance of solar protons coincided with

Forbush effects and in seven cases, with the sudden commencement of geomagnetic storms. It was discovered that the intensity of electrons was never (excepting February 5-13 event) more than that of protons with $\mathcal{E}_p > 500$ kev. The nature of the recorded low-energy protons and the nature of their propagation in the interplanetary medium are described in short.

Results of measurements, conducted simultaneously on satellite "IMP-2" (launched in October 1964), "IMP-3" (launched in May 1965) and on spaceship "Mariner-4", are given in the work of O'Gallagher and Simpson [127]. The equipment, installed on these satellites, facilitated separation of beams of protons and helium nuclei in the range $\mathcal{E}_k = 1$-170 Mev/nucleon.

The observed data on flux of protons with $\mathcal{E}_k > 1$ and $\mathcal{E}_k > 15$ Mev are interpreted by authors [127] in the following way.

1. In some cases, protons from solar flares propagate in strictly limited space regions which have the same characteristics as the rotating sectors of interplanetary magnetic field. Moreover, proton beams take part in the rotation.

2. This anisotropy of propagation is very strongly related to the spectral structure of the magnetic field. If the difference in longitudes between the central meridian and the region of chromospheric flare is more than or approximately equal to 40°, the particles cannot reach the Earth.

3. Beams of low-energy protons, recorded in other experiments with 27-day cycle, can exist during a few revolutions of the Sun and they diffuse up to a distance of 71.5 astronomical units.

Measurements of O'Gallagher and Simpson [127] were made during the minimum solar activity; therefore, the effects observed in 1965 have much lesser value than those measured on the satellite "IMP-1" in 1964. List of the cases of increases recorded in 1965 along with the data on solar activity is given in Table 11.1. Amongst all the observed events, following are the most interesting.

TABLE 11.1

Cases of increase in the intensity of low-energy particles based on the observations in 1965 on "Mariner-4", "IMP-2" and "IMP-3"

Period of increase, UT		Relation with solar flares
"Mariner-4"	"IMP-2" and "IMP-3"	
20.00 Jan. 8 - 04.00 Jan. 13	10.00 Jan. 8 - 00.00 Jan. 11	Not detected
18.47 Feb. 5 - 02.00 Feb. 12	18.40 Feb. 5 - Feb. 9	Class 2^+ flare, 17.00 Feb. 5, 8°N, 125°W
23.50 May 25 - 04.00 May 28	Observations not made	X-ray flare, May 25, 22.41, 19°N, 69°W
02.00 June 1 - 10.00 June 4	Not detected	Not detected
20.00 June 5 - 10.00 June 9	20.00 June 5 - 08.00 June 7	X-ray flare and radio emission of type IV, June 5, 18.25, 12°S, 50°W
04.00 June 13 - unspecified	08.00 June 13 - unspecified	Class 2^+, flare, June 9, 06.00, 22° N, 45°E
10.00 June 15 - 10.00 June 19	16 and June 16	Class 2 flare, June 15, 07.35, 22°N, 30°W
Not detected	21.00 June 17 - 04.00 June 18	Not detected
12.00 June 29 - 18.00 July 2	06.00 June 30 - 20.00 July 1	Class 2^+ flare, June 28, 10.20, 33°N, 36°E
22.00 July 5 - 22.00 July 6	04.00 July 6 - 08.00 July 6	Not detected
15.00 July 14 - unspecified	Not detected	Not detected
04.00 August 4 - 20.00 August 4	Not detected	Not detected
10.00 August 7 - 02.00 August 11	Not detected	Not detected
Not detected	14.00 August 16 - 20.00 August 18	Class 2 flare, August 15, 06.15, 35°S, 75°W
04.00 August 27 - unspecified	00.00 Sept. 1 - 12.00 Sept. 4	Not detected
10.00 Sept. 22 - 04.00 Sept. 26	00.20 Sept. 27 - 23.00 Sept. 30	Not detected

First of all, the increase recorded on the 228th day of 1965 is of great interest. Protons from the powerful solar flare, situated at 75° west of the Sun-"IMP-3" line easily reached this satellite. But the instruments on "Mariner-4" situated at 40° towards east of "IMP-3" did not record any increase. This east-west effect testifies to the strong anisotropy of propagation of solar protons in the interplanetary magnetic fields. Another case of this type (219th day of 1965) is less defined since, on this day, optical flare on the Sun was not detected. Proton beam in this case reached "Mariner-4" but was not recorded on "IMP-3".

Events of another type are related to propagation of solar protons together with the rotating magnetic fields. Increase in proton intensity, recorded by "Mariner-4" on the 180th day, was preceded by class 2 solar flare which occurred 24 hours earlier at 36° east of the Earth-Sun line. This increase was recorded on "IMP-3" about 0.7 day later. The difference between the calculated time of rotation of particle beam in the interplanetary field (~ 1.9 day) and the experimentally obtained time (0.7 day) is apparently caused by lateral diffusion. Another event of this type (164th day) is possibly related to solar flare but we cannot say it with certainity.

Finally, increase in the flux of solar protons with 27-day cycle should be put under the third type of events. It has been shown for these events that they cannot be caused by solar flares. For example, increase on "Mariner-4" on the 239th day was recorded on "IMP-3" 4.7 days later which well agrees with the calculated time of rotation of the corresponding beam of particles (nearly 4 days). The increase on "Mariner-4" (265th day) is another example of this type of event. Table 11.2 shows the expected (if velocity of solar wind ~ 400 km/sec) and observed differences in the times of recording the increases on "Mariner-4" and the Earth's satellites "IMP-2" and "IMP-3".

It was shown by the measurements of Bryant et al. [119] that increases in the intensity of protons, repeating every 27 days, were weak and probably, could not be detected by riometers. Actually, as mentioned by Gregory and Newdick [129], riometers in this case become insensitive. According to

TABLE 11.2

Differences in the times of recording the increases in protons flux on "Mariner-4" and the Earth's satellites "IMP-2" and "IMP-3"

No. of solar revolution	Day of first detection on "Mariner-4" (1965)	Expected time of rotation in days	Observed time of rotation of beam of particles in days	Possible source of protons
1804	164	1.0	0.4 ± 0.2	Solar flare
1805	180	1.9	0.7 ± 0.2	Solar flare
1806	216	2.9	Time of rotation for secondary peaks within the limits of time profile of intensity	27-day recurrence
1807	239	4.0	4.7 ± 0.3	27-day recurrence
1808	265	5.2	5.5 ± 0.4	27-day recurrence

Gregory [11.13], ionospheric data on minimum reflection frequencies f_{min} or data on partial reflection from the ionosphere is the best indicator of weak proton beams. On the basis of these data, Gregory and Newdick [129], independent of other research workers, arrived at the conclusion that solar proton beams repeat on the Earth after first, second and, possibly, subsequent revolutions of the Sun.

In connection with the detection, by Gregory [II.13], of the fact that solar protons are generated by small chromospheric flares and in general, by the active Sun, it becomes necessary to get a universal identification of every recurring beam. From this follows the requirement that patrol of solar flares should be almost continuous and not even a single small flare should occur during at least 24 hours before measuring the flux on the Earth. The flare event of September 28, 1961 was the first one satisfying this criterion.

Measurements on f_{min} were made at the stations Scot-Base (79°S), Cape Hallet (75°S) and Resolute (83°N). On the basis of the obtained data, Gregory and Newdick [129] arrived at the conclusion that slow protons during September 28, 1961 flare were captured in the trap with angular dimensions of 20° in the ecliptic plane and slowly came out of it.

In the work of Bryant et al. [119], it is assumed that the increase in the flux of slow protons in the interplanetary space on September 7, 1961 was caused by a chromospheric flare on the invisible side of the Sun. Data obtained by Gregory and Newdick [129] confirm that this increase is related to a 54-day recurrence of the beam which was for the first time observed on July 12-17, 1961. The low-flux event of February was apparently a repetition of the January 11-14, 1960 event.

There arises one question: are the observed recurrent phenomena caused by continuous emission of protons with $\mathcal{E}_k \lesssim 15$ Mev from active regions of the Sun or are these particles emitted at different short intervals and later captured in magnetic traps of interplanetary space? More thorough investigations than those possible from data on minimum reflection frequencies (f_{min}) are necessary for finding an answer to this question.

Interesting data on low-energy primary particles were obtained by Hofmann and Winckler [130]. Measurements were made on May 12, 1965 (i.e. during minimum solar activity) with the help of a scintillation detector which was flown on a balloon over Barrow (Alaska) and drifted to an altitude with pressure of 3.5-5 g/cm^3 during 26 hours. The detector facilitated separation of isotopes of hydrogen and helium nuclei in the primary radiation. The spectrum of protons in the range $\mathcal{E}_k$ = 70-150 Mev, upper limit of the flux of primary deuterons [$0.1\ m^{-2}\ sec^{-1}\ sterad^{-1}\ (Mev/nucleon)^{-1}$] in the energy range of 45 - 60 Mev/nucleon and spectrum of primary He^3 nuclei in the range of 90-150 Mev/nucleon were obtained in the work. It was established that $He^3/(He^3 + He^4)$ ratio is 0.11 ± 0.05 and 0.15 ± 0.01 at energies of 100 and 120 Mev/nucleon respectively (or 0.34 ± 0.09 at a rigidity of 0.8 Gv). These data are in agreement with the results of satellite measurements of Fan et al. [11.35] in the same energy range.

Fan et al. [131] studied the anisotropy and fluctuation of the flux of solar protons with $\mathcal{E}_k$ = 0.6-100 Mev from the data of measurements on "Pioneer-6" during the period December 29, 1965-January 4, 1966. Comparing the obtained results with the conclusions drawn in works [119, 135], Fan et al. [131] do not eliminate the possibility that a large portion of low-energy protons was accelerated not during flares but during other types of processes. However the problem of the effectiveness of acceleration of particles by magnetic fields of interplanetary space still remains unsolved.

Measurements on protons of solar origin with $\mathcal{E}_k$ = 1-5 Mev, made by a group of Soviet research workers under the guidance of S.N. Vernov [132] during the flight of "Venera-2" "Venera-3" and "Zond-3" probes, are of great interest.

Six events of significant increases in the flux of protons were recorded during the flight of interplanetary automatic stations "Zond-3", "Venera-2" and "Venera-3" launched on July 18, November 12 and November 12, 1965 respectively. Three of these events were recorded by "Zond-3", two by "Venera-2" and one by all the three stations.

All the cases of the above-mentioned increases in the intensity of protons with $\mathcal{E}_k = 1\text{-}5$ Mev are shown in Figs. 11.3-11.6. In addition to the data of proton detectors and gas-discharge counters, 4-hour data of neutron monitor at Deep River and values of K_p-index of magnetic disturbance are also given on these Figs.

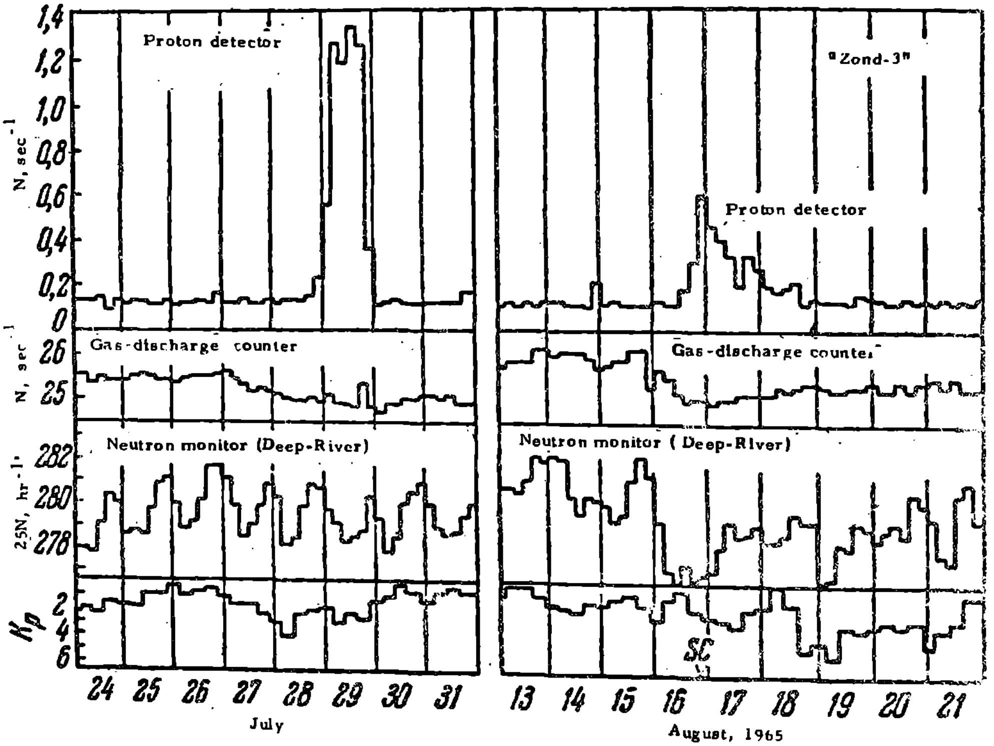

Fig. 11. 3. Outbursts of low-energy protons on July 29, and August 1965 from the data of station "Zond-3".

The first two outbursts were observed on July 29 and August 16-17, 1965 (Fig. 11.3). According to data of neutron monitor and gas-discharge counter on "Zond-3", small Forbush decreases in the intensity of cosmic rays were observed in both the cases. Apparently, the Earth and the station "Zond-3" during this period existed in the corpuscular beam.

Significant increase in the intensity of protons with $\mathcal{E}_k = 1\text{-}5$ Mev on July 29, 1965, lasting for about one day, took place

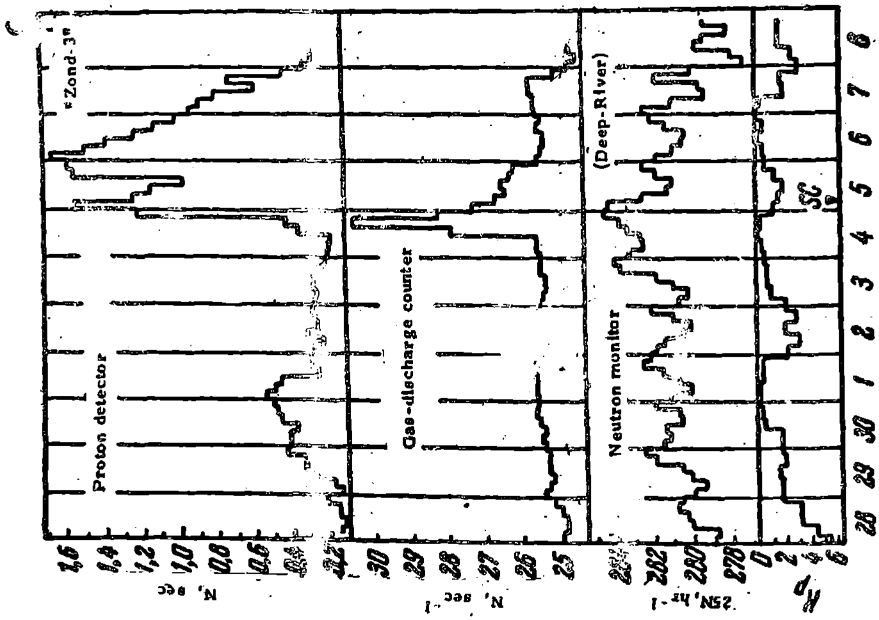

Fig. 11.4. Outbursts of low-energy protons on October 4, 1965 from the data of station "Zond-3".

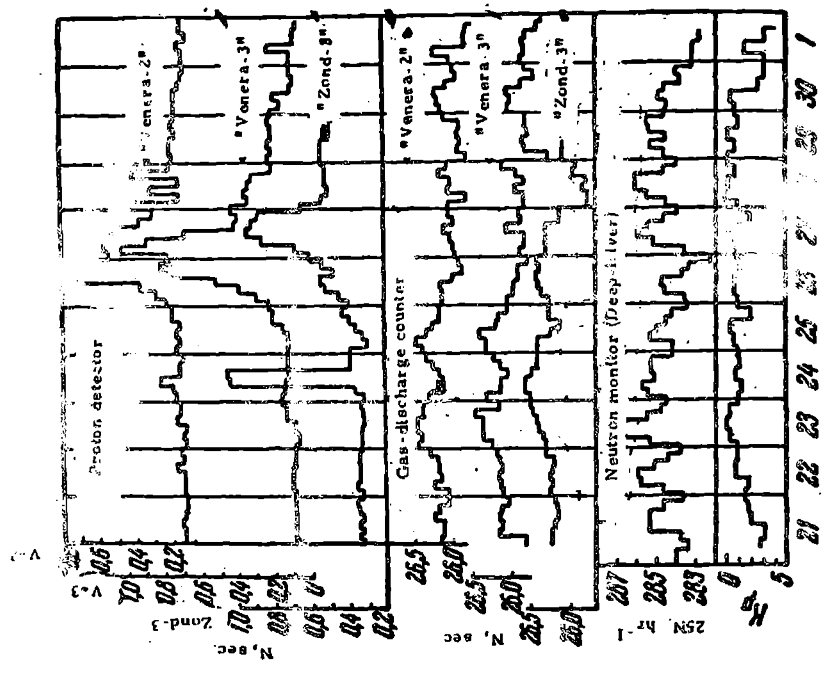

Fig. 11.5. Outbursts of low-energy protons on November 27, 1965 from the data of stations "Venera-2", "Venera-3" and "Zond-3"

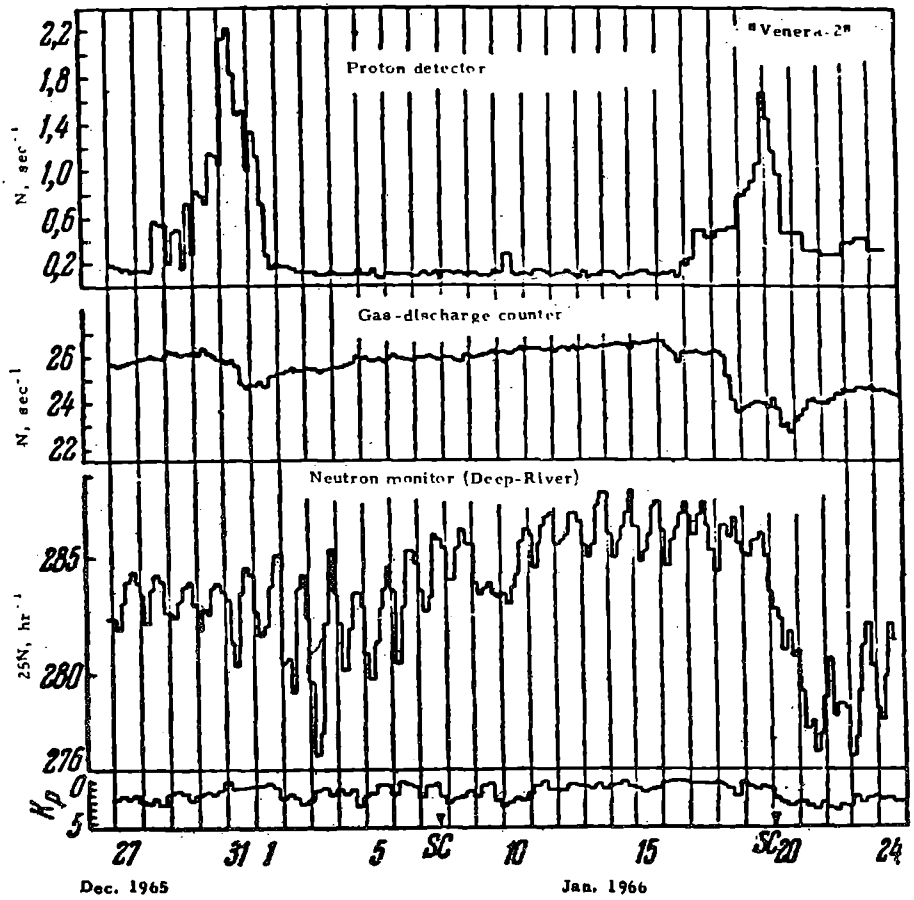

Fig. 11.6. Outbursts of low-energy protons during December 28, 1965 - Jaunary 2, 1966 and January 18-24, 1966 from the data of station "Venera-2".

two days after the entry of the Earth and the "Zond-3" in the corpuscular beam. Further observations on "Zond-3" and "Venera-2" showed that during six subsequent revolutions of the sun, the active region, responsible for July 29 outburst, did not inject 1-5 Mev protons.

August 16-17, 1965 outburst was apparently caused by the active region of the Sun with coordinates 25°N, 90°W. If it is assumed that solar protons move along Archimedean spirals of the interplanetary magnetic field, the velocity of corpuscular beam in this case is found to be equal to 220 km/

sec. The outburst of August 16-17, 1965 was accompanied by a magnetic storm with sudden commencement.

Fig. 11.4 shows the third outburst which was accompanied by an increase in the flux of penetrating protons ($\mathcal{E}_p \gg 40$ Mev) recorded by gas-discharge counter. During this event, probably protons with $\mathcal{E} > 1$ Gev propagated to the Earth which is confirmed by the increase in the reading of neutron monitor at Deep River.

As may be seen from Fig. 11.4, the third increase has a very complicated profile. This increase started in the end of September and continued up to October 8, 1965. The active region, which appeared on the Sun at 0715 UT on September 26 (20°N 90°E) existed right up to 0735 UT on October 8, 1965 (22°N, 76°W). During this period one class 2^+ flare, six class 2 flares, twelve class 1 flares and many weaker flares were observed in this region. Moreover, another class 2 flare was observed at 0935 UT in another active region which on October 4 had the coordinates 22°S, 29°W. However, as shown in [132], these flares cannot be responsible for the appearance of 1-5 Mev protons which could have moved along Archimedean spiral corresponding to radial plasma speed of 200-400 km/sec.

Fig. 11.5 shows the data on increase in the intensity of 1-5 Mev protons on November 27, 1965, recorded on three interplanetary probes : "Venera-2","Venera-3" and "Zond-3" The distance between the probes "Venera-2" and "Venera-3" at that time was 10^6 km. The observed displacement of maximum of the increase on "Venera-3" as compared to "Venera-2" can be explained by the fact that the period of rotation of "Venera-3" was much more than the average interval of data which could lead to some modulation in the counting rate of "Venera-3". Additional modulation due to probe rotation apparently could not change the time of steep front of increase in the intensity and therefore, as expected, sudden increase was simultaneous on "Venera-2" and "Venera-3". (The period of rotation of these probes was much less than the average time).

During the November 27, 1965 outburst, probes "Venera-2" and "Zond-3" were situated in such a way that the corpuscular beam in the beginning reached "Venera-2" and then "Zond-3", the velocity of the beam being less than 350 km/sec.

An analysis of Fig. 11.5 helps in drawing the following picture of the process of acceleration and propagation of 1-5 Mev protons in the interplanetary space [132].

Protons are accelerated on the Sun and move along lines of force of the magnetic field, twisted along an Archimedean spiral. On November 24, 1965, there was very weak beam of protons at the line of force passing through "Venera-2" and a beam of very high intensity at the line of force passing through "Zond-3". On November 26, 1965, there appeared a strong beam of particles at the line of force passing through "Venera-2" and "Venera-3". At that very time, much weaker beam appeared at the line of force passing through "Zond-3". This flare lasted for more than one day and the sudden increase on "Zond-3" on November 27, 1965 can be interpreted as transmission of a line of force to "Zond-3" highly enriched with protons and leading to November 26, 1965 increase on "Venera-2" and "Venera-3". This gives rise to a velocity of 220 km/sec of the corpuscular beam. The width of beams consisting of 1-5 Mev protons is of the order of 3×10^{12} cm.

Let us assume that the minimum of the intensity of cosmic rays, recorded by counter on "Venera-2" and "Venera-3" on November 24, 1965, is caused by corpuscular beam. Then, from the time lag ($\sim$ 24 min) of minimum intensity at "Zond-3" with respect to "Venera-2" and "Venera-3", it follows that the average velocity of this beam is equal to 200 km/sec. On the other hand, from the fact that the width of this minimum on "Zond-3" is more than that on "Venera-2" and "Venera-3", it follows that the velocity of the beam decreases with time from 290 to 190 km/sec at width of the beam equal to 10^{13} cm. Such low velocities of plasma have not been observed up to this time by direct methods.

It should be pointed out that the velocities of beams obtained in [132] were determined from the pitch of the assumed Archimedean spiral. But the structure of the magnetic field may not precisely correspond to this picture. The spiral probably gets deformed due to nonuniform ejection of particles from a given active region on the Sun as well as due to interaction of magnetic fibers of the neighboring regions. The possibility should also not be eliminated that as the plasma moves away from the Sun, its velocity deviates from the radial direction and has a tendency to orient along the magnetic field. In this case, the pitch of the spiral will continuously decrease with increase in distance from the Sun. This picture satisfactorily explains the experimental data on time lag without leading to abnormal plasma speeds of ~ 200 km/sec and permitting the speed of 300 km/sec or more which was many times observed by direct measurements.

Fig. 11.6 shows data of two more increases in the intensity of protons observed during December 28, 1965-January 2, 1966 and January 18-24, 1966. Noticeable duration of these two increases compared to the previous ones which is possibly related to superimposition of many flares from neighboring active regions on the Sun cannot be ignored. Significant Forbush-decreases (especially on January 18-24, 1966) recorded by Geiger counter on "Venera-2" confirm it.

By comparing the above-mentioned events of the increase in the flux of 1-5 Mev protons during the flight of "Venera-2" "Venera-3" and "Zond-3" probes, it can apparently be concluded that August 16-17, 1965 and December 28, 1965-January 2, 1966 events are related to the same active region while September 29-October 4, November 27, 1965 and January 18-24, 1966 events, to another region on the Sun which is common for all the three events.

On the basis of the obtained results, S.N. Vernov et al. [132] arrive at the conclusion that the Sun generates not only high-energy protons but also, very often, low-energy protons (1-5 Mev).

In most of the cases, high-energy protons propagate in the interplanetary space by diffusion. As is obvious from Figs. 11.3-11.6, time dependence of the intensity of 1-5 Mev protons sometimes differ much from that for diffusion process. Thus, at least near the minimum solar activity, 1-5 Mev, protons propagate in the interplanetary space along the lines of force. This conclusion is confirmed by the measurements of Bartley et al. [133] and McCracken and Ness [134] who showed that the angular distribution of protons with $\mathcal{E}_k = 7.5$-45 Mev is anisotropic and their velocities are usually directed away from the Sun.

If the corpuscular beam has magnetic field whose lines of force extend up to the active region on the Sun, low-energy protons generated in this region freely move in a spiral along the lines of force of the magnetic field. Thus, the corpuscular beam creates some tunnel along which comparatively low-energy protons can leave the Sun and attain regions situated at significant distances from the Sun.

This assumption is confirmed by the data obtained by Fan et al. [135] in 1964 on the satellite "Explorer-18" ("IMP-1"). The increase in the intensity of low-energy protons was recorded on this satellite every 27 days during many successive revolutions of the Sun which points out the continuous disappearance of these protons from one active region of the Sun in the corpuscular beam. However, experimental results obtained by S. N. Vernov et al. [132] allow one to assume that the emission of protons often lasts for less than one revolution of the Sun. Obviously, the active regions do not always generate protons or create conditions for their exit from the source periodically (and sometimes, for a long time).

With the aid of satellite "IMP-1" Fan et al. [135] in 1964 conducted measurements on beams of protons with $\mathcal{E}_k > 1$ Mev during six consecutive 27-day intervals and each of the beams was observed for a few days. The energy spectra of protons was measured at the beginning and at the end of appearance of the beam. In the same beam, particles with spectrum of the type $\sim \mathcal{E}_k^{-2}$ in the energy range of 2-30 Mev/nucleon were detected. Data of the satellite "OGO-1" [135] confirm the fact that beams of protons and α-particles were observed not only within the regions rotating along with the Sun but constantly exist in the interplanetary space (with lesser intensity and other spectra) for 2.5 months. Possible mechanisms of continuous acceleration of protons and α-particles are discussed in [135]. Description of the apparatus installed on "IMP-1" was published by Fan et al. [136] earlier.

At present, there are direct proofs of the fact that the interplanetary magnetic field changes the direction and increases in intensity almost at the same time when a beam of low-energy protons appears. Wilcox and Ness [137] discovered that regions of intensified magnetic field appear simultaneously with a change in its sign. Fan et al. [135] show that there are always proton beams in the interplanetary space which rotate along with the Sun independent of the direction of the field.

Differential spectra of protons obtained in the end of 1963 [135] are shown in Fig. 11.7. It is seen that spectrum in the leading part of the beam is more rigid ($\sim\mathcal{E}_k^{-4}$) than in the lagging part ($\sim\mathcal{E}_k^{-5}$).

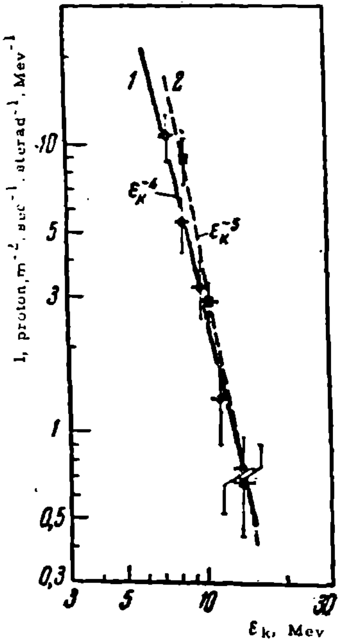

Fig. 11.7. Spectra of low-energy protons from the data of "IMP-1" in December 1963:
1 - in the leading part of the beam; 2 - in the lagging part of the beam.

The spectra of helium (α-particles) from Galaxy for $\mathcal{E}_k > 7$ Mev/nucleon were studied by Fan et al. [135] on the satellites "IMP-1" and "IMP-2". It was discovered that inclination of the spectrum changes sign at $\mathcal{E}_k \approx 20$ Mev/nucleon. This indicates the presence of an additional flux of helium at low energies and that the appearance of this flux possesses a 27-day cycle. A telescope, facilitating recording of protons and helium nuclei with $\mathcal{E}_k$ = 1-35 Mev/nucleon in the presence of cosmic ray back-ground was installed on the satellite "IMP-1" [135].

Although the amplitude of 27-day variation was very small in the end of 1964 (minimum solar activity), Fan et al. [135] could ascertain this variation many times and also during October 18-19, 1964 event. This period too is characterized by changes in neutron intensity (from the data on ground monitors) and increase in the flux of protons with $\mathcal{E}_k > 1$ Mev/nucleon (from the data of "IMP-2"). The spectra of protons ($\mathcal{E}_k^{-3.6}$) and helium nuclei ($\mathcal{E}_k^{-2.2}$) on October 19, 1964 are shown in Fig. 11.8. Similar spectra were also obtained on November 16-17, 1964. For comparison, the spectrum of helium nuclei ($\mathcal{E}_k^{0.88}$) in primary cosmic radiation, measured on satellite "OGO-1" is shown in Fig. 11.8. In all, five similar events were recorded. These results along with the data of "IMP-2" show that helium nuclei are related to beams of protons in the regions rotating along with the Sun.

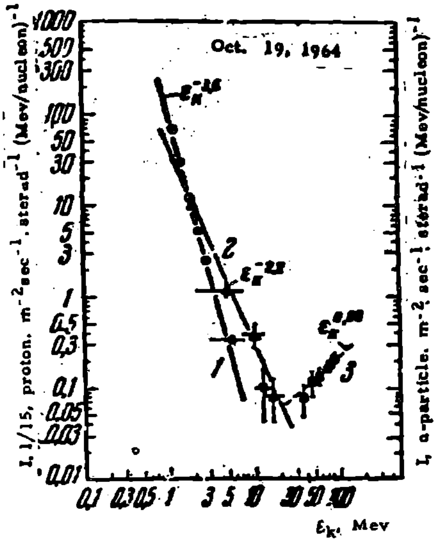

Fig. 11.8. Spectra of protons and low-energy α-particles on October 19, 1964 from the data of "IMP-1", "IMP-2" and "OGO-1":
1 - protons; 2 - low-energy α-particles; 3 - α-particles of galactic cosmic rays.

Judging from "IMP-1" data, there are no low-energy protons in between these regions. However, subsequent measurements on "OGO-1" showed that beams of protons and particles of very low intensity were always present in the interplanetary space in the end of 1964. These beams were recorded by "IMP-1" instruments as a weak background. The spectra of protons ($\mathcal{E}_k^{-6}$) and helium ($\mathcal{E}_k^{-2}$) for the quiet period on December 16, 1964 are shown in Fig. 11.9 as an example. A similar picture was observed in all the 16 cases of measurements during the period October 15-December 15, 1964.

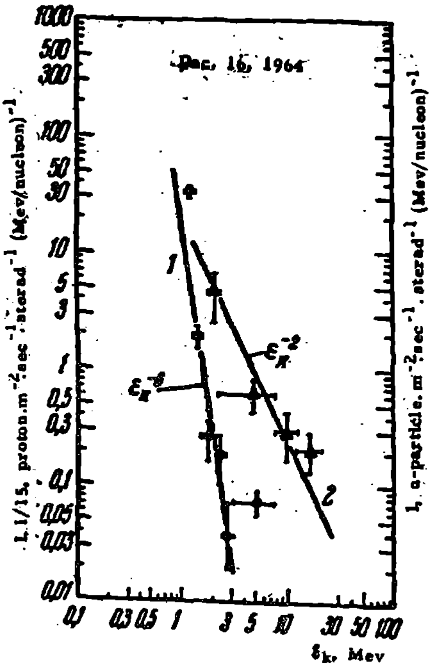

Fig. 11.9. Spectra of protons and low-energy α-particles in December 16, 1964 from the data of "OGO-1":
1 - protons; 2 - α-particles.

If protons in the rotating region have the spectrum with $\gamma \sim 3.5$, then $\gamma \sim 5$-6 outside this region and the intensity of particles in the latter case is significantly low. On the other hand, index of the spectrum in the rotating region and outside it changes only from 2 to 3 for helium. Thus, whole of the obtained data is satisfactorily described by the spectrum of the type $\mathcal{E}_k^{-\gamma}$ where γ is measured in Mev/nucleon.

The presence of low-energy helium component in the interplanetary space, which, with the passage of time, is correlated to changes in the spectrum and intensity of low-energy protons, convincingly confirms that the origin of these components is the same. The question arises whether they have galactic origin or appear in the solar system? In this connection, attention is drawn to the fact that, according to Fan et al. [135], on about December 1, 1964, the flux of helium nuclei of galactic origin in the region of very low energies increased by about 1.5 times. On the other hand, it may be seen from Fig. 11.9 that significant increase in the flux of helium nuclei with ε_k = 1-30 Mev/nucleon was not observed during October-December 1964 (quiet period). This can serve as an argument against diffusion of α-particles from the Galaxy.

The possibility of acceleration of particles in the solar system appears to be more probable: either near the Sun in the regions with strong magnetic field or in the interplanetary space in the rotating structure of the field or in the region of interaction with irregular magnetic fields beyond the limits of the Earth's orbit.

The particles accelerated in these processes by diffusion and convection gradually fill the solar system and go out in the Galaxy. The changes, observed with the passage of time, in the intensity and spectrum of protons and helium must be defined by the properties of the "source" which must be sufficiently powerful to retain the dynamic equilibrium of the particles in the solar system during the minimum solar activity. In this connection, it may be interesting to study the operation of this source in the period of high solar activity and its ability to generate particles with $\varepsilon_k \gtrsim 100$ Mev/nucleon and spectrum similar to one observed in 1961 by Vogt [138] in the range of 80-300 Mev/nucleon.

It is also significant to explain the reason why there is no increase in the flux of protons and helium in the regions (which are identified on the basis of direct measurements of magnetic fields and plasma or from the data on modulation of cosmic rays) rotating along with the Sun. Moreover, the existence of stable space structure of proton beams helps in assuming the possibility of continuous disappearance of protons along magnetic channels from the Sun. In view of this, the assumption of solar acceleration of the observed particles is more preferable.

11.2. Possibility of accumulation of solar particles in the interplanetary space. Due to scattering at irregularities of the interplanetary field, the average holding time of solar particles in the solar system during high solar activity increases to a few days. It is obvious, for example, from the data of stratospheric and riometric observations.

Since, during high activity, the interval between flares generating cosmic rays, is considerably less than the holding time of particles in the interplanetary space, there will be accumulation of low-energy protons and nuclei. High-energy particles will be retained for a very short period due to high diffusion coefficient $\varkappa$ since the holding time $\sim L^2/\varkappa$ where L denotes the system dimensions. The mean free path for scattering of particles and average interval between flares increase with a decrease in the activity which must lead to a significant decrease in the intensity of solar particles in the interplanetary space.

The spiral type quasiregular magnetic field can play a great role in holding the particles in the solar system. The presence of such a field beyond the Earth's orbit (where the tanegntial component of the field is significant) leads to the fact that the solar particles exit, transverse to the magnetic field, and the characteristic exit time increases to tens of days.

Data, obtained by Meyer and Vogt [139] can serve as an indication to the fact that the fraction of captured solar particles in the range $\mathcal{E}_k \lesssim 300$ Mev is significant. Measurements on $\mathcal{E}_k \gtrsim 80$ Mev protons were conducted during six balloon flights in July-August 1961 at geomagnetic latitudes $\geqslant 73°$N. A comparison of the obtained data with the results of 1960-measurements shows that 1) there is always a significant flux of low-energy protons in the primary cosmic radiation during the years of high solar activity; 2) if the flux of galactic cosmic rays in the region of low energies (particularly in the region of maximum spectrum $\sim$ 400-600 Mev) increases (by 20-30% during 1960-61 which is in agreement with other experimental data) with the decrease in the solar activity, the flux of $\mathcal{E}_k \lesssim 200$ Mev protons, on the other hand, decreases with a decrease in solar activity (by about 30% during the same period). It follows from this that the proton beams, observed in [139], have solar origin.

In principle, these protons could have been generated not by chromospheric flares (and later on, held in the interplanetary space) but continuously as a result of some acceleration processes in the chromosphere or in the corona of the Sun (and in this case, capture of particles is not a must). If the first cause is the main one, the spectrum of constant beam of solar protons must be softer than that of protons emitted during flares; if continuous generation of protons is the basic cause, then the spectrum of captured protons can have no relation whatsoever with the spectrum of protons from flares.

July 22, 1961 measurements gave the differential spectrum of the form $\sim \mathcal{E}_k^{-4}$ (after July 18, 1961 solar flare which had increased the intensity of cosmic rays even on the Earth's surface), the July 27, 1961 measurements gave the spectrum of the form $\sim \mathcal{E}_k^{-2.5}$ and August 1, 6 and 8, 1961 measurements gave the spectrum $\mathcal{E}_k^{-2}$ (stable beam of trapped protons had an intensity of about 1.2×10^4 $\mathcal{E}_k^{-2}$ proton.m^{2}. sec^{-1}. sterad^{-1}. Mev^{-1}).

What is the reason that with the passage of time, the spectrum becomes not softer as is expected in the case of generation of particles during flares and propagation by diffusion mechanism but, on the other hand, becomes more rigid? This can be explained by the presence, in addition to the diffusion, of convection of particles from the Sun due to increase in the radial distance of irregularities from the Sun (according to Section 14.9, the lesser the energy of particles, the greater will be the role of convection) or by the significant decrease in the inclination of the spectrum of particles, generated during flares, on transition to lesser energies (see Section 8.1). Nevertheless, the above-mentioned results do not eliminate the second alternative that the trapped protons are continuously generated by the Sun and that their spectrum can be much more rigid than that of protons during flares. In this case, it is possible that, as a result of this continuous generation, the Sun gives a more or less constant flux of protons and that the observed decrease in their intensity with a decrease in solar activity is related to weakening of scattering in the interplanetary space*.

Very important results were obtained by Stone [140] from the December 13, 1961 measurement data on low-energy protons. Measurements were made with the help of a counting telescope with nine crystal diode detectors aboard the satellite "Discoverer-36" having polar orbit (launched at 2202 UT on December 12, 1961; inclination of the orbit to the equatorial plane 81.21°; period of revolution 91.82 min; height at perigee 241 km and at apogee 489 km). The equipment facilitated separation of protons from α-particles in the energy range of 10-250 Mev/nucleon.

The results of the experiment were very limited due to many drawbacks in the operation of satellite transmitter. Nevertheless, reliable data were obtained for December 13, 1961 flare which were in conformity with the results [139] for 80-130 Mev range and which showed the presence of protons with energies right up to 10 Mev. The intesnity of protons in the range 10-85 Mev was $\sim 1 m^{-2} sec^{-1} . sterad^{-1} . Mev^{-1}$. This value is much less than the flux which can be obtained by extrapolating in the low-energy range of spectrum of the form $\mathcal{E}_k^{-2}$ observed by other research workers [139; I.23] at $\mathcal{E}_k$ = 90-200 Mev.

Thus, the spectrum of 10-85 Mev protons during quiet periods is more plane than $\mathcal{E}_k^{-2}$. Table 11.3 shows the data

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* *Considering the possibility of existence of low-energy background, Parker [I.61] solved the diffusion equation for the quasistable case (i.e., on the assumption that the particles are generated by the Sun either continuously or sporadically but very often, with constant intensity). According to [I.61], the average rate of generation of particles on the Sun at* $\varkappa$= $5x10^{21}$ cm^2/sec *must be* ~ $2x10^{25}$ *particle/sec which corresponds to a liberation of energy* ~ $4x10^{21}$ *erg/sec. Intensity of 80-350 Mev protons, recorded by Vogt [138] was 0.02 particle.*$cm^{-2} . sec^{-1} . sterad^{-1}$ *which corresponds to a concentration of* $2x10^{-11}$ cm^{-3}. *Taking the average life of particles in the solar system to be equal to 10 days, Vogt [138] found* 10^{20} *erg/sec as the approximate value of the rate of liberation of energy. During observations from July to September 1960, the average number of class 1 flares on the visible side of the Sun during one day was* ~ *6 and of class 2 flares, nearly 0.4. If the flares on the invisible side of Sun appear at the same frequency of about* $0.143x10^{-3}$ sec^{-1} *(one flare every* $7x10^3$ *sec) and if during every flare, particles, on an average, liberate energy of about* $3x10^{25}$ *erg, we get the observed constant background of low-energy particles.*

TABLE 11.3

Data on low-energy particles on the basis of measurements made on the satellite "Discoverer-36" [140]

Energy, Mev/nucleon	Number of observations	Corrections for nuclear interactions	Geometrical correction	Intensity, $m^{-2} \cdot sec^{-1} \cdot sterad^{-1} \cdot Mev^{-1}$
		Protons		
11 - 18	1	0	0	$1.6^{+3.7}_{-1.3}$
18 - 27	2	0	0	$2.8^{+3.5}_{-1.8}$
27 - 60	2	0	0	$0.9^{+1.1}_{-0.6}$
60 - 125	7	-2	-1	$0.6^{+0.7}_{-0.4}$
		α-particles		
>560	8	0	0	120^{+60}_{-40}
>80	16	0	0	240^{+80}_{-60}

obtained in the polar region (65°) over which the satellite passed after 1518 seconds.

From the emulsion measurements on ballons over Churchill on July 8, 1961, Fichtel and Guss [141] and Fichtel et al. [42] obtained the intensity of α-particles I (>100 Mev/nucleon) = $205 \pm 11 m^{-2}.sec^{-1}.sterad^{-1}$ and I (>600 Mev/nucleon) = $151 \pm 11 m^{-2} sec^{-1}, sterad^{-1}$. In both the cases, measurements were preceded by at least 10-day periods of zero solar activity. Solar activity before Stone's observations [140] was also very low and therefore, the reasonable coincidence of all the three measurements strenghtens the reliability of data obtained in [140].

On December 1, 1961, Bryant et al. [119] recorded a recurrent beam of low-energy protons. All the geophysical effects associated with this ended by December 4. No solar radio outbursts were observed during the next 10 days; the number of solar protons was very low and only 6 small chromospheric flares were observed. Thus, protons observed on December 13, 1961 correspond to the quiet beam.

The spectrum of low-energy protons, obtained by Stone [140] on December 13, 1961, is shown in Fig. 11.10. In the

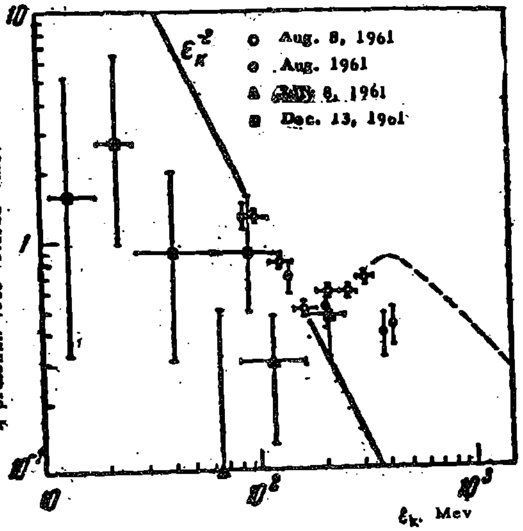

Fig. 11.10. Spectrum of December 13, 1961 low-energy protons in comparison with results of other measurements. Differential spectrum of galactic cosmic rays is shown by dotted line.

same Fig. are shown the spectra for higher energies obtained by Meyer and Vogt [139] on August 8, 1961 and By Bryant et al [123] in August 1961 with the help of counting telescopes as well as spectra of Fichtel and Guss [141] obtained on July 8, 1961 from the data of photoemulsions. All these data refer to periods which were not preceded by large solar flares. Results of counter measurements in the region of high energies are similar to each other but differ from the results of emulsion measurements.

Important results on protons with ε_k = 80-200 Mev were obtained by Freier and Waddington [142] from the data of emulsion measurements on balloons over Churchill on August 26, 1960. The upper limit 53 ± 6 $m^{-2}.sec^{-1}.sterad^{-1}$ of the intensity of protons on this day significantly differs from the measurement results of Vogt [138] who on August 22 and September 15, 1960 observed a proton beam with intensity of about 121 ± 6 $m^{-2}.sec^{-1}.sterad^{-1}$. Vogt [138] also conducted observations in stratosphere over Churchill but a sodium iodide crystal served as the detector of particles in this case.

The differential spectra of protons obtained in 1960 by Vogt [138] and Freier and Waddington [142] are shown on Fig. 11.11, a. The light symbols show the data of photoemulsions while the dark symbols show the results of counter measurements. It is very important to mention that the value of the intensity obtained from emulsion data is actually the upper limit since the intensity of secondary protons, formed in air over the detector, was not subtracted from the measurement data. In this connection, Freier and Waddington put forward the suggestion that the decrease in the intensity of low-energy protons, observed in a number of experiments after 1960, was caused not by a decrease in the primary flux of these protons but only by the introduction of correction for secondary particles.

All the published results on the measurement of flux of low-energy protons during the years 1961, 1962 and 1963 are given in Figs. 11.11, b,c and d. The results of Meyer and Vogt [139] Fichtel et al. [142], Bryant et al. [I. 23] and Stone [140] are represented in Fig. 11.11, b. Fig. 11.11, c gives the measurement data of Meyer and Vogt

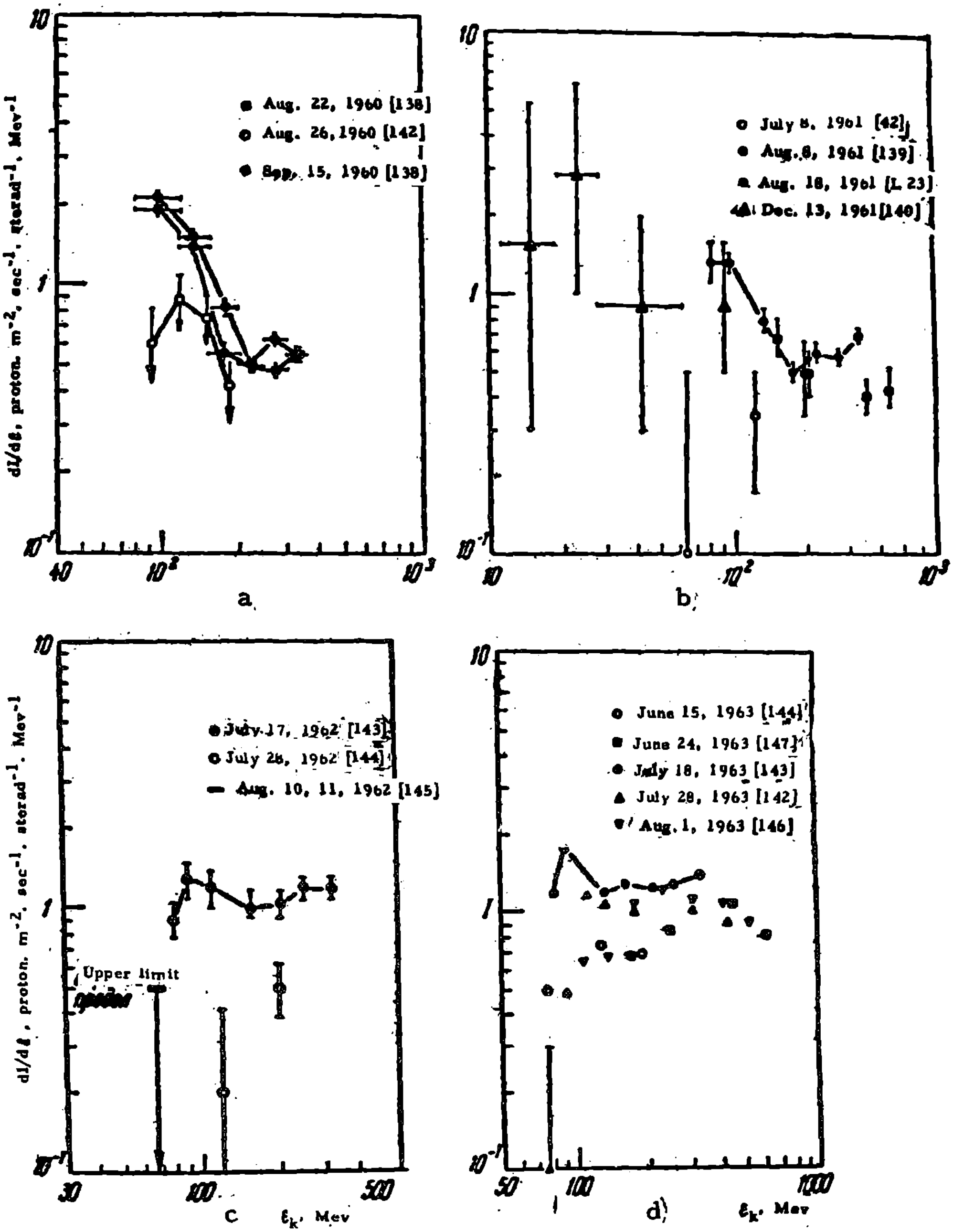

Fig. 11. 11. Differential spectra of low-energy protons from measurements in:
a - 1960; b - 1961; c - 1962; d - 1963.

[143], Fichtel et al. [144] and Brunstein [145]. The results of Meyer and Vogt [143], Ormes and Webber [146], Freier and waddington [142], Fichtel et al. [144] and Balasubrahmanyan and McDonold [147] are shown in Fig. 11.11, d.

It may be seen from Fig. 11.11 that high flux of protons with $\varepsilon_k \lesssim 150$ Mev, confirmed by Vogt in 1960 and 1961, was not recorded in any of the experiments except by Stone [140] in 1961. The four points obtained by Stone represent the sum of 12 particles and therefore, in the opinion of Freier and Waddington [142] the problem of separation of primary protons from the secondary ones cannot apparently be solved with the help of statistics.

Thus, the problem of the possibility of accumulation of low-energy protons in the interplanetary space up to this time remains unsolved. However, there is no doubt that some background of protons with energies of the order of tens of Mev and less can exist in the interplanetary space. It is evident from the data of numerous direct measurements on rockets and satellites (see Section 11.1) even during periods close to minimum solar activity*.

B. M. Vladimirskii [148] gives interesting arguments in favor of the assumption about solar origin of the flux of particles with $\varepsilon_k \lesssim 200$ Mev, detected by Vogt [138] and Meyer and Vogt [139]. In this connection, it is first of all, appropriate to mention the following.

During the study of effects of solar flares in cosmic rays, it was believed that there exists a special class of "proton" flares accompanied, during their development, by acceleration of protons and nuclei to high energies. According to this point of view, the remaining solar flares are not associated with emission of solar cosmic rays. However, numerous experiments conducted by different authors showed that the boundary between these two groups of flares is more quantitative that qualitative. On the other hand, much progress in the observational methods (in particular, riometric observations) and more detailed analysis of previous data pointed to a clearly-observed tendency of widening the class of "proton" flares due to more and more weaker effects.

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*At the international symposium on solar activity (Budapest, September 1967), M. Pick [V. 189] reported the data on protons with $\varepsilon_k = 0.6-13$ Mev and $\varepsilon_k > 50$ Mev recorded in the interplanetary space by probes "Pioneer-6" and "Pioneer-7" in 1966. In 1-10 Mev range, differential spectrum of protons was of the form $\sim \varepsilon_k^{-2.5}$ and $\varepsilon_k^{-2.8}$ on August 27, 1966 and August 20-23, 1966 respectively ("Pioneer-7"). According to the data of "Pioneer-6", the spectrum of protons with energy 10-100 Mev in the period 1501-1916 UT on March 20, 1966 was of the form $D(\varepsilon_k) = 1.8 \times 10^7 \varepsilon_k^{-8}$ m^{-2} sec^{-1} $sterad^{-1}$ Mev^{-1}.

Recently, it became clear that some of the effects could not be recorded on the Earth even with the aid of ionospheric observations in the polar cap. Moreover, some of the flare effects could have been masked by modulation processes in the solar system. Due to this, the class of "proton" flares should be wider. Insufficiency of experimental data on small effects, for the first time detected in 1954 by Freier [I. 7], did not facilitate their comparison with large effects. Due to this, the spectra of particles, responsible for small effects, appeared to be cut off near $\mathcal{E}_k \sim 10^8$ ev which differentiated these effects from large increases usually accompanied by powerful polar absorptions.

As already mentioned, measurements made by Vogt [138] during previous years pointed out a stable beam of particles with $\mathcal{E}_k < 200$ Mev which was not of galactic origin. These results are confirmed by the measurements of Stone [140] and Bryant et al. [I. 23]. B. M. Vladimirskii [148] tried to substantiate the assumption that this stable constant beam is the "tail" of the energy spectrum of particles from small increases.

According to the estimates of L. I. Dorman and E. V. Kolomeets and G. A. Sergeeva [150], the spectrum of particles during small outbursts in 3-20 Gev range does not significantly differ from the spectra of large outbursts. It has been established for most of the cases that the spectrum is diffused in the region of low energies.

Let us show that flux of particles from small outbursts should be practically constant for $\mathcal{E}_k < 200$ Mev. It has been established that small effects of the outbursts are apparently related to all the flares which are accompanied by the short-lived effects in the D-layer of the ionosphere observed at medium latitudes (see Section 5). According to Hachenburg and Krüger [150], 70-80% of class 2 flares and about 20% of class 1 flares are accompanied by Delinger effect. The frequency of such events during Vogt's measurements [138] was one flare every 16 hours. Moreover, according to Biswas et al. [I. 24], the exponential law of decrease in the intensity with time constant equal to 22 ± 2 hours for $\mathcal{E}_k < 200$ Mev protons can be used for the measurement period [138]. Then the intensity after any effect decreases by not more than 50% before the beginning of the next effect. If there exist such flares whose spectrum is not diffused in the relativistic region, the fluctuations will of course be still smaller. The average spectrum of this type of particles must be similar to the spectrum observed about 16 hours after the commencement of a large increase.

Fig. 11.12 shows the dependence of characteristic rigidity R_0 on time for the flares on February 23, 1956, July 16, 1959, May 4, 1960, November 12 and 15, 1960 and on July 18, 1961. The spectrum in this case has the form (8.8); values of R_0 are taken from the work of Freier and Webber [6] while the time along the ordinate is counted from the time of beginning of the outburst at sea level. If the data of Vogt [138] are represented in a similar way, we get $dI/dR = 8.2 \exp(-R/180)[m^{-2}, sec^{-1}, sterad^{-1}, Mv^{-1}]$. The value $R_0 = 180$ Mev is marked on Fig. 11.12 by a cross. It may be noticed that the position of this point satisfactorily

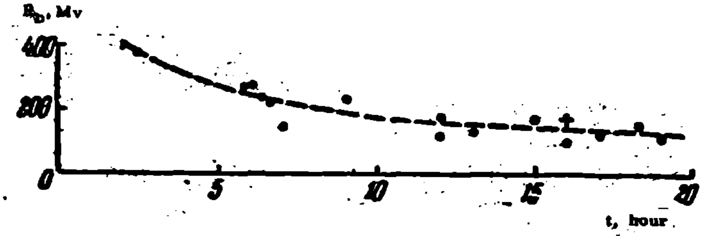

Fig. 11.12. Dependence of characteristic rigidity R_0 of the spectrum of solar comic rays on time, counted from the beginning of the effect at sea level. The value R_0 = 180 Mv is marked by a cross.

corresponds to the adopted average frequency of the flares (1/16 hour^{-1}).

The existence of a constant flux of protons in the energy range under reference must lead to the presence of constant additional ionization in the polar ionosphere. Such an effect was actually detected by Gregori [152]. Calculations given by B. M. Vladimirskii [148], for the profile of electron concentration corresponding to the above-obtained spectrum, give large deviations from Gergori's experimental data [152] (see Table 11.4):

TABLE 11.4

Comparison of calculated [148] and measured [152] electron concentration in polar ionosphere

Altitude, km	$n_e(p)$ [148]	$n_e(p+\alpha)$ [148]	n_e [152]
80	130	160	2
85	100	130	55
90	80	110	100
100	35	50	200

The calculations [148] were made for the case when the beam of solar particles consisted of only protons as well as for the beam containing α-particles. The accuracy of calculations corresponds to an error of about ± 50%. The accuracy of Gregori's experimental data [152] is apparently even lesser. Thus, based on the given analysis, it is not possible to answer the question as to whether the continuous beam of solar comic rays is the main source of ionization in D-layer of the polar ionosphere at night and as to whether the ionospheric data can be used as an indicator of this beam.

Determination of nuclear composition of the beam of particles at rigidity less than 0.6 Gv is very important for the study of the effects of small increases. However, all the spectra of α-particles in 1957-58 were obtained after strong solar flares and therefore, it was impossible to conclude about the constantly existing beam of α-particles on the basis of these measurements [148].

A significant role of solar component should be expected in the observed charge distribution at high energies ($R \leqslant 1$ Gv) especially of rare nuclei. It can be illustrated on the example of He^3 isotope which, as assumed, was detected recently in galactic cosmic rays. As mentioned above, a significant concentration of He^3 nuclei was detected by Schaefler and Zähringer [I.56] for November 12, 1960 flare and the ratio He^3: $p \sim 0.1$. If such a concentration of He^3 isotope is considered to be typical of flares and if the spectrum obtained in [148] is extrapolated to R=1 Gv, the intensity of the beam from the Sun will be $\sim 3.3 \times 10^{-3}$ m^{-2}. sec^{-1}. $sterad^{-1}$. Mv^{-1}. On the other hand, at the same rigidity and basing on the $He^3/(He^3+He^4) \sim 0.2$-$0.3$ (Apparao [153], Foster and Malvey [154]) and intensity of α-particles (Engler et al.[155]) we get the value of $(8 \pm 4) \times 10^{-3} m^{-2}$. sec^{-1}. $sterad^{-1}$. Mv^{-1}. This rough estimate shows that it is not at all eliminated that the whole of He^3 in this region of spectrum is of solar origin.

It can thus be concluded that the flares, responsible for small effects of the outburst at sea level, can be taken as very weak "proton" flares. The following argument can be cited in favor of this conclusion. It was established that, on an average, there is a rough proportionality between the value of flare effect, power of radio emission in the centimeter range and intensity of X-ray on radiation. But the frequency of distribution of these effects according to power monotonically increases on transition to weaker effects. For example, according to Takakura [156], amplitude distribution function of radio emission $\lambda = 10$ cm has the form $A (> I) = kI^{-0.75}$. The distribution of X-ray radiation according to frequency can be represented in a similar way. It is natural to assume that the distribution function of flares according to the number of accelerated protons and nuclei is a characteristic feature of most (if not all) of the chromospheric flares.

Small effects of increases in the intensity of cosmic rays after chromospheric flares were till recently studied in the region $\mathcal{E} \gtrsim$ Gev. The study of weak effects in the region of low energies also is obviously of interest.

By analyzing the effects of flares of $\geq$ class 1^+ from the data of stratospheric measurements over Murmansk during June 1957-June 1964, B.M. Vladimirskii [157] detected an increase of 3-4% in the intensity of protons (the effect was also observed at the latitude of Mirny). The observed effect in the region of low energies was foretold by L.I. Dorman ([1.1], Section 21). The amplitude of increase $\sim$ 3-4% corresponds to the flux of about 0.6 cm^{-2} sec^{-1} of the particles with $\mathcal{E}_k \gtrsim 100$ Mev. Such a value of flux corresponds to the average interval of time 4.5 hours after the commencement of solar flare and is apparently the maximum. Since the intensity after attaining the maximum for this energy range decreases with time constant $T_0 \approx 22$ hours (which is comparable to the frequency of class 1^+ flares in 1957-59), it was concluded in [157] that there should be a constant, although intensly fluctuating, flux of solar comic rays during the period of maximum activity. This conclusion is the indirect proof of the results of measurement [138, 139] and their interpretation. Apparently, cosmic rays are generated in practically all the cases during small flares. It is important to mention [157] that the mean free path spectrum for absorption of protons, giving rise to small effect, was similar to the spectrum observed after large flares, for example on May 4, 1960. It testifies to the similarity of integral energy spectra of solar particles for effects of both the types.

12. SOLAR FLARES AND LUMINESCENCE OF THE MOON AND THE MERCURY

12.1 Luminescence of the Moon. On the night of November 1-2, 1963, Kopal and Rackham [158] at Pic du Midi Observatory (France) obtained photographs of the Moon from which two instances of intensification of red radiation of a large portion of the lunar surface near the Kepler crater were detected. This portion occupied about 1/60th part of the lunar surface and the radiation intensity in red light was more than the brightness of the remaining surface of the Moon by 86 ± 3 %. It is about ten times the luminescence effects observed at any other place on the Moon by other research workers.

The observed phenomena are of great interest for scientists studying the problems of cosmophysics. It is well known that the Moon is subjected to the action of visible, ultraviolet and X-ray radiation of the Sun and is also bombarded by galactic cosmic rays and high-energy solar particles. Its surface is not protected from external action by the atmospheric layer and therefore, it can be expected that the Moon will luminesce.

Such an assumption was for the first time put forward by Czech astronomer F. Link in 1946 who, on the above basis, tried to explain the apparent surplus radiation in the region of the Earth's shadow on the Moon during some lunar eclipses. He attributed this radiation to the effect of ultraviolet radiation of solar corona or to the action of high-energy charged particles which move from the Sun along bent trajectories. These two types of radiations are subjected to the "shadow effect" of the Earth to a much lesser extent than the visible solar light.

During the last part of fifties, N.A. Kozyrev in the USSR and J. Duby in France obtained spectroscopic proofs of the lunar luminescence. The observation method was borrowed by them from Link and they detected, among the dark lines of the reflected solar light, lines of lunar origin on the spectrospectrograms, N.A. Kozyrev in 1961 put forward the hypothesis about the existence of active volcanos in the region hypothesis about the existence of active volcanos in the region of lunar craters. Recently, most-detailed measurements were made by Greindzher and Ring at the Asiago Observatory (USA). They showed that the llminescence goes up to 10% of the intensity of solar light in the ultraviolet line of ionized calcium.

The laboratory experiment of Derkhem and Jack (Manchestor, England) is closely related to these measurements in which they subjected a typical type of meteorite to proton bombardment in an accelerator. In this experiment, a bright illumination was observed in a wide range of wavelengths near 6700 Å (red line). The possibility is not eliminated that a similar illumination can be observed at different sections of the lunar surface where there is accumulation of meteoritic substances. Apparently, these accumulations should be expected in the region of lunar craters formed due to the falling of big meteorities.

How to explain the phenomenon observed by Kopal and Rackham ? First of all, the assumption about the internal, lunar origin of the observed effect should be rejected. The huge area with high brightness and small duration of the effect (~ 15-20 min) would require a high speed of propagation of every disturbance along the lunar surface. As suggested by Kopal and Rackham, solar activity can be the only cause of the observed phenomenon.

Among other appearances of solar activity on November 1, 1963, two small solar flares were observed in the same active region with heliocordinates of 0^{o}N and 25^{o}W during 1356-1407 and 1545-1605 UT respectively. The interval between these two flares (about 2 hours) approximately corresponds to the interval between two increases in red radiation in the region of the Kepler crater. The effects on the Moon were observed about 8.5 hours after the flares on the Sun, i.e., the effect of X-ray radiation of these flares is absolutely eliminated. It remains to suppose that the illumination was caused by the solar corpuscular radiation of concentration 500 cm^{-3}, propagating at a speed of about 5000 km/sec. It corresponds to energy density of about 10^{-11} erg/cm^3.

Going beyond the framework of Kopal and Rackham observations, it should be mentioned that excitation of red illumination of the lunar surface can also be expected during sudden increases in the intensity of solar cosmic rays. As mentioned in Chapter II, the energy density of solar cosmic rays in different cases is 10^{-9} erg/cm^3, i.e., about 100 times the above-obtained value. Moreover, owing to propagation of solar cosmic rays by diffusion, the "shadow effect" of the Earth during lunar eclipses will not have a significant effect on their intensity at the Moon's orbit. Due to the same reason, the effect of solar flares can apparently be observed when the Moon is incomplete. It will be of interest to record illumination of lunar surface at new Moon. The particles of very low-energies can reach the lunar surface since the Moon does not have significant magnetic field and is devoid of atmosphere. It follows from this that the effect of solar flares can be ascertained from the observations on lunar surface even in cases when the solar particles of not very high energies fail to reach the Earth due to inclined effect of the geomagnetic field and due to absorption in the Earth's atmosphere.

Interesting effects should also be expected when the Moon is enveloped by solar corpuscular beams which give rise to geomagnetic storms, polar auroras and other geophysical phenomena.

Thus, if the observations of Kopal and Rackham get further confirmation, new possibilities will open before research workers of cosmic space for qualitative and quantitative correction and widening of modern concepts about the nature of processes on the lunar surface on the Sun and in the interplanetary space. This method of investigation will be very effective in organizing a systematic "lunar service" with the help of the world network of observatories or artificial satellites of the Moon, especially, during the years of high solar activity.

12.2. Possible effect of luminescence of the Mercury. If the luminescence is caused by solar wind, it is also of interest to study the other bodies in the solar system (for example, Mercury) which just like the Moon are not protected by atmosphere.

The fluctuatations in the brightness of different sections of the Mercury surface were detected in 1935 by Antoniadi who considered the darkness visible on the surface of the planet as a result of variations in the cloudy cover. On the basis of numerous observations with the help of 33" Medon reflector, Antoniadi arrived at the conclusion that the density and extent of clouds change with a change in the distance of the Mercury from the Sun. The changes probably attain the maximum value at the perigee and minimum at apogee.

The 55 ± 5 terrestrial day period of rotation of the Mercury, obtained by Pettengil and Dyce [160] gives rise to certain doubts about the long-duration changes described by Antoniadi since his conclusions were based on the assumption of 88-day period. Even in 1935, Antoniadi [159] drew attention to the fact that the changes on the Mercury take place during tens of hours and that it cannot be explained only on the basis of a shorter period of rotation. Other observers also mention short-duration changes in the brightness on the Mercury surface.

During the years 1958-64, Cruickshank [161] made a large number of observations on the Mercury with the help of telescopes of aperture of 82 inches. Visual observations of the Mercury are difficult due to its proximity to the Sun. Nevertheless, the results obtained by Cruickshank, in general, confirm that the changes in the brightness of certain sections of the Mercury surface can actually take place during a few hours or days.

The great similarity between the Moon and the Mercury which was mentioned by many research workers and the possible luminescence phenomena on the Moon makes it possible to interpret the changes on the Mercury as the luminescence effects of the materials on its surface.

Good [162] paid much attention to the fact that the flux of solar protons near the Earth's orbit depends on the position of the Mercury. Cases of arrival of protons to the Earth from solar protons were observed more often when the Mercury existed in-between the Sun and the Earth and was projected on the Sun within the bands with heliocoordinates of 20°N-20°S where the flares are more often accompanied by the ejection of a large amount of fast protons. Good estimated the magnetic field of the Mercury at equator: $H_M \approx 3x10^{-3}$ gauss which is much less than the Earth's field $H_E \sim 0.5$ gauss. As assumed in [162], the magnetic field of the Mercury can bend the trajectory of solar protons and thus, can increase the number of particles reaching the Earth.

12.3. Possible mechanisms of lunar luminescence.

Possible mechanisms of the lunar luminescence, in terms of the known sources of excitation and with consideration of energy requirements, are studied in detail in the work of Ney et al.

[163]. In particular, it is pointed out that such sources as hard ultraviolet, soft ultraviolet scattered by the Earth, solar wind, tail of the Earth's magnetosphere and solar cosmic rays should give rise to illumination of the same order. Galactic cosmic rays play a smaller role in luminescence.

Regarding observations of Kopal and Rackham [158], the authors [163] mention that the interference filters used in [158] are characterized by nonuniformity of transmission of image from the center to the edges. This fact is significant for observations [158] since the luminescent regions detected by Kopal and Rackham are on the corner of the photographs. It is not clear from the data published by them if the possible sources of systematic errors have been eliminated and therefore, in the opinion of the authors [163], the results [158] are not very convincing. Ney et al. [163] arrive at the conclusion that the most significant luminescence should be expected on the dark side of the Moon and during full lunar eclipses. If the luminescence is visible on the illuminated side of the Moon, ultraviolet radiation of the Sun must be the only external source. If the mechanisms of accumulation of solar energy function on the Moon, there is a possibility of thermal luminescence and only spectroscopic observations can provide the proof of the reality of lunar luminescence.

CHAPTER IV

PROPAGATION OF SOLAR COSMIC RAYS IN THE INTERPLENETARY SPACE

The propagation of solar cosmic rays in the interplanetary space is analyzed in this Chapter. This process is governed by the interplanetary magnetic field which apparently consists of two components-- quasiregular and irregular. Relative importance of each of these is determined by the energy of particles. Irregularities of the interplanetary field mainly affect the movement of medium and high-energy particles. This effect leads to scattering which can approximately be described by different diffusion models. Quasiregular component of the field apparently plays the leading role in the region of low energies. Motion of a particle along the line of force should be explained by the model of the guiding center. If scattering by irregularities becomes significant, it becomes necessary to resort to more complicated mathematical means. The distribution of a large number of particles in space can more accurately be described on the basis of the kinetic equation.

Modern concepts on magnetic fields in the interplanetary space and motion of charged particles are described below and diffusion and kinetic propagation models are considered in detail. Effect of the properties of the source (generation spectrum, duration of emission, heliocoordinates of the flare) and dynamics of interplanetary medium (movement of magnetic irregularities from the Sun) on space -- time distribution of solar particles is evaulated.

13. SOLAR COSMIC RAYS AND MAGNETIC FIELDS IN THE INTERPLANETARY SPACE

13.1 Possible role of interstellar field. Attention of research workers to this question was drawn for the first time in connection with the February 23, 1956 flare. Ehmert [1] assumed that the particles emitted, by the Sun, propagate in the intenstellar magnetic field in a specific direction. The trajectory of particles was calculated on the assumption that this field is homogeneous and directed at an angle φ to the Earth-Sun line and that the particles are emitted from the Sun isotropically. Particles emitted at a small angle to the field are more isotropic, cover lesser path and reach the Earth quicker than the particles emitted at a large angle.

Ehmert finds that, in order to explain the observational results, intensity of the interstellar field, homogeneous in the region of the solar system, should be of the order of 7×10^{-7} gauss and the angle $\varphi \approx 30^{\circ}$, while the lines of field should reach the Earth from a point with coordinates $\alpha = 12$ hrs 00 min and $\delta \approx 30^{\circ}$N. It coincides with the direction of galactic spiral sleeve containing the solar system. Intensity of the field amounting to 7×10^{-7} gauss is in agreement with the estimate of Fermi and Chandershekar, obtained from the data on polarization of light from stars.

However, this picture encounters serious difficulties. In particular, even the author himself mentions that the measured values of the flux of solar particles in the stratosphere which show that the particles with $\mathcal{E} = 1-15$ Gev reached the Earth immediately after the noon and evening of February 23, 1956, contradict his concept, according to which particles with $\mathcal{E} < 7.5$ Gev should not reach the Earth. In the opinion of the author, the above observation leads to either $\varphi \approx 0^{\circ}$ (although, in this case, there arise some other difficulties) or the particles of such low energies are generated in the Earth's surroundings.

There are a number of other difficulties mentioned by Alfven, Gold et al. regarding the work under reference:

1. If the solar flare appears at that time when the interstellar field is perpendicular to the Sun-Earth line (for example, as during July 25, 1946 flare), effect of the flare should not be observed on the Earth.

2. Ejecting action of solar corpuscular beams and solar wind on the interstellar field must be taken into account.

3. In the presence of the interstellar field, the particles, during the decrease of the flux according to the law t^{-2}, should have propagated from a plane and not isotropically as was observed.

A similar model is considered in the work of Cocconi et al. [2]. The space between the Sun and the Earth is supposed to be filled by uniform magnetic field parallel to the Earth-Sun line. The source of cosmic rays here is not the Sun, but a plane perpendicular to the magnetic field and situated at the same distance as the Sun. Relativistic particles will move along spirals and the time of their propagation to the Earth $t \approx 8$ min/cos θ, where θ is the angle between the direction of motion of the particle and magnetic field. The time t increases with an increase in θ and it can explain the delay of particles recorded on the Earth outside the shock zones. The authors [2] consider that extension of the Sun's general magnetic field, frozen in the corpuscular beams, can give rise to the interplanetary field which is close in its properties to the one considered in this model.

Possibly, the question of the effect of the interstellar field on the dynamical processes in the interplanetary medium and on the motion of particles in the solar system has to be reconsidered in the light of new observational data. In this connection, attention is drawn by the conclusion of I. I. Pronik's [3] work that the interstellar magnetic field near the solar system is not the homogeneous field of the galactic sleeve as was considered earlier but has a much complicated structure.

Interstellar magnetic field in the Sun's surroundings is extremely irregular. The field is stretched along the line of sight above the plane of the Galaxy in a direction with galactic longitude $\ell'' \sim 75^{\circ}$ and below the plane of the Galaxy in a direction with galactic longitude $\ell'' \sim 15^{\circ}$. Lower and upper fields are inclined at 60° to each other. The field is not directed along the line of sight below the plane of the Galaxy in the direction $\ell'' \sim 75^{\circ}$ coinciding with one of the directions of the Orionov spiral branch. This result is obtained from the data on polarization of the star light as well as from the observations on the movements of the clouds of the interstellar calcium.

Two systems of magnetic field are observed in the Sun's surroundings. Both the fields are far from being plane. The pole related to the system of one field is situated in the external region of the Galaxy and the pole of the second field, in the internal region of the Galaxy, i.e., both the fields are not parallel to the plane of the Galaxy. Angle of inclination of the fields on different galactic longitudes changes from 20 to 40-60° with respect to the plane of the Galaxy.

13.2 Movement of solar particles in the quasiradial magnetic field. For a given spectrum of solar particles, their propagation from the Sun to the Earth is mainly controlled by the interplanetary magnetic field.

The study of large outbursts of solar cosmic rays led to the concept of the existence of irregularities in the interplanetary field at which the particles get scattered. Subsequent investigations on flares and direct measurements with space rockets and satellites showed that there is also a weak regular quasiradial field in the space between the Sun and the Earth. The general characteristics of the interplanetary field can be conveniently studied by monitoring solar particles since it has a significant effect on the delay, direction of arrival and degree of anisotropy of particles.

Anisotropy of solar particles from ground data. Interesting results on anisotropy were obtained by McCracken [4] who studied propagation of protons from solar flares in November 1960. According to [4], solar protons moved along twisted lines of force from a direction in space, about 50° towards west of the Earth-Sun line. It corresponds to Parker's model [I. 61] for quiet interplanetary field which arises as a result of pulling of the Sun's total field by quiet solar wind at an average velocity of 3×10^7 cm/sec. However the direction of motion of protons was spread over an angle of about 40° which indicates multiple scattering during their propagation from the Sun to the Earth along the lines of force. This scattering reveals the existence of irregularities in the regular quasiradial field.

Similar results ~~were~~ obtained by McCracken [4] for May 4, 1960 flare. Eight flares recorded by ground detectors and about 30 events detected from the data on absorption of short radio waves were studied in this work. The times of arrival to the Earth, of solar particles with $\mathcal{E}_k$= 10-100 Mev during large chromospheric flares are investigated.

In the work of G.F. Krymskii and A.I. Kuz'min [5]. The events selected for analysis were obtained from absorption of radio waves in the polar caps. The comparisons of these events with heliolatitude distribution of 29 flares showed that particles from flares in the northern hemisphere of the Sun have much lesser delay (6.6 hours) than those from flares in the southern hemisphere (14.9 hours). Such an asymmetry is also observed from the data on solar particle flux at the Earth's surface. If the asymmetry is caused by a difference in diffusion of particles, it is necessary to assume that the lines of force of the quasiradial magnetic field connect the Earth to the north-western part of the solar disk instead of the western part.

Analysis of July 18, 1961 flare, done by A.I. Kuz'min et al. [6] on the basis of the ground data, showed that solar particles came from directions making an angle of 50-60° with the west of the Sun-Earth line. The July 20 outburst, caused by the flare on the western limb of the Sun, was characterized by significant anisotropy observed as clearly-marked shock zones on the Earth's surface.

Deviation of the beam of solar particles towards the west of the Earth-Sun line was also observed on the Earth's surface for many other flares of cosmic rays. It is important to mention that in this case, there is gradual "erosion" of the beam with the passage of time till it becomes isotropic.

Investigations conducted during the past years showed that displacement of shock zones mentioned in Section 3.7 is, first of all, related to curvature of the interplanetary field due to the rotation of the Sun. Analysis of cosmic ray flares in the stratosphere and investigations on polar cap absorption of short radio waves also lead to the same result.

Direct measurements of interplanetary field. The measurements on interplanetary magnetic field were, for the first time, made in 1960 by Kopal et al. [7] with the help of the satellite "Pioneer-5" (also see the work of Greenstadt [8]). By the same satellite, Arnoldy et al. [9] recorded the April 1, 1960 flare of cosmic rays whose analysis showed the presence of irregularities in the field. Data on interplanetary magnetic field at distances up to 1.9×10^6 km from the Earth were obtained by Sh. Sh. Dolginov et al. [10] while making measurements with the automatic interplanetary probe "Venera-1" launched in February 1961.

Presence of quasiradial interplanetaryfield, coiled into Archimedean spiral, was, for the first time, confirmed by the direct measurements of Heppner et al. [11] made in March 1961 with the satellite "Explorer-10" having an intensly elongated orbit.

In 1962, Snyder and Neugebaner [III. 118] made detailed measurements on cosmic rays and interplanetary magnetic fields with the help of satellite "Mariner-2". Measurements [11; III. 118] confirmed the assumption of the presence of irregularities in the interplanetary field. It follows from the data of Heppner et al. [11] that irregularities of the field have characteristic dimensions of 3x10 cm and at $H = 2 \times 10^{-4}$ gauss, should significantly scatter particles of rigidity 10 Gv. This does not contradict the estimates made from the data on solar cosmic rays. According to E.I. Mogilevskii [12] these irregularities can have forceless structure.

According to the same data, [11] regular component of the interplanetary field, very stable during quiet periods, has an intensity of $H \approx 3 \times 10^{-4}$ gauss and is directed almost radially from the Sun with a deviation of $30-40^{\circ}$ caused by rotation of the Sun.

Data on magnetic measurements, taken by Ness et al. [13] with the help of satellite "IMP-1" in the end of 1963, apparently indicate the fibrous structure of the interplanetary field. There are also other proofs in favor of the complicated structure of the interplanetary magnetic field. Most of these proofs were obtained from the analysis of different types of variations in galactic cosmic rays [I. 2].

Davis et al [14] give results of the magnetometric data obtained by "Mariner-4" for the space between the orbits of the Earth and the Mars during the period November 29, 1964 -- November 30, 1965. Measurements confirmed the presence of the expected spiral structure of the magnetic field, which gives rise to the observed nonsinusoidal fluctuations. On averaging, these fluctuations were reduced to zero. Analysis of the data did not confirm the presence of a component of the average field directed towards the South. Spectral analysis of data obtained during about two weeks shows that the amplitude of magnetic fluctuations, in the frequency range $f = 10^{-4}$-$3x10^{-3}$ Hz and in the coordinate system related to solar wind, is of the order of $10^{-3.2\pm0.3} f^{-5/3}$ gamma^2/hertz. Data [14] help in getting spectra for other periods and frequencies right up to 0.5 Hz which corresponds to noise threshold of the apparatus*.

In the end of 1964, 4-sector field was observed with the help of "Mariner-4" which was similar to the field detected by Wilcox and Ness [III. 137] from the data of "IMP-1" for the period December 1963-February 1964. This structure of the field differs very much from the 2-sector structure observed on "Mariner-2" in 1962. According to the data of "Mariner-4", sectors became less defined in the beginning of 1961 than in the end of 1964.

Measurement of anisotropy in the interplanetary space.

Bertley et al. [III. 133] took detailed measurements on low-energy solar particles with the help of space satellite "Pioneer-6". The cosmic-ray detector, installed on "Pioneer-6", facilitated recording of particles from four directions of the ecliptic plane and protons were measured in the energy ranges of 7.5-45 Mev, 45-90 Mev and 150-350 Mev while the nuclei with $Z \geqslant 2$ were measured only in 150-350 Mev range. The detector which recorded protons with ε_k =7.5-45 Mev, could also record electrons with ε_k =7.5-13 Mev. Instrument errors in the determination of fluxes were of the order of 10^{-5} and thus, the detector could record very weak anisotropy starting from 10^{-4}. The amplitude, direction and spectrum of anisotropy of low-energy solar cosmic rays were studied and characteristics of small-scale irregularities of interplanetary field were also evaluated.

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* *Data, obtained on "Mariner-4" on the intensity of cosmic rays (measurements by shielded counters sensitive to electrons with $\mathcal{E}_k \geqslant 1$ Mev and protons with $\mathcal{E}_k \geqslant 10$ Mev) were used by McCoy and Anderson [129] for studying variations having periods of 2-200 minutes. The obtained power spectrum of variations can be interpreted as an indication of the presence of local structure of the field and hydromagnetic waves in the interplanetary medium. The observed modulation ($\pm 5\%$ of the average intensity) is caused by structural elements having characteristic dimensions of $5x10^9$-$5x10^{11}$ cm.*

The analysis of a large number of cosmic-ray flares, recorded by the space probe "Pioneer-6", indicates the presence of very strong anisotropy observed for particles with an average energy of about 13 Mev. Direction of the anisotropy undergoes significant and sudden changes while the maximum solar flux was often found to be from the antisolar direction. It was found that the direction of anisotropy is well related to the changes in the interplanetary field. A model of interplanetary field is being developed according to which particles of low-energy solar cosmic rays move along well-defined and curved fibers of the magnetic field, submerged in the solar wind. The curved fibers have diameters up to 3×10^6 km. It is shown that field in the fibers is sufficiently regular to the extent to which it can be judged from the data on anisotropy of 13 Mev protons. Proofs of continuous injection of solar particles for about 48 hours were obtained from the same data.

Most characteristic features of the three outbursts of cosmic rays, which were observed during the first 30 days, starting from December 16, 1965, after the launching of "Pioneer-6", are described below.

Data from "Pioneer-6" averaged for every 7.5 minutes and 2-hours data of neutron monitor at Churchill during the period December 26, 1965-January 5, 1965 are shown in Fig. 13.1. Two outbursts on December 27 and 29, 1965 are clearly seen which resemble the "classical" flares of cosmic rays with quick increase and slow decrease in the intensity. Class 2 flare with coordinates 10°N, 59° W was observed at 1124 UT before December 29, 1965 outburst. The outburst which started on December 30, 1965 had a more complicated nature and it was preceded by class 1^+ flare at 0006 UT with coordinates 09°N., 71°W.

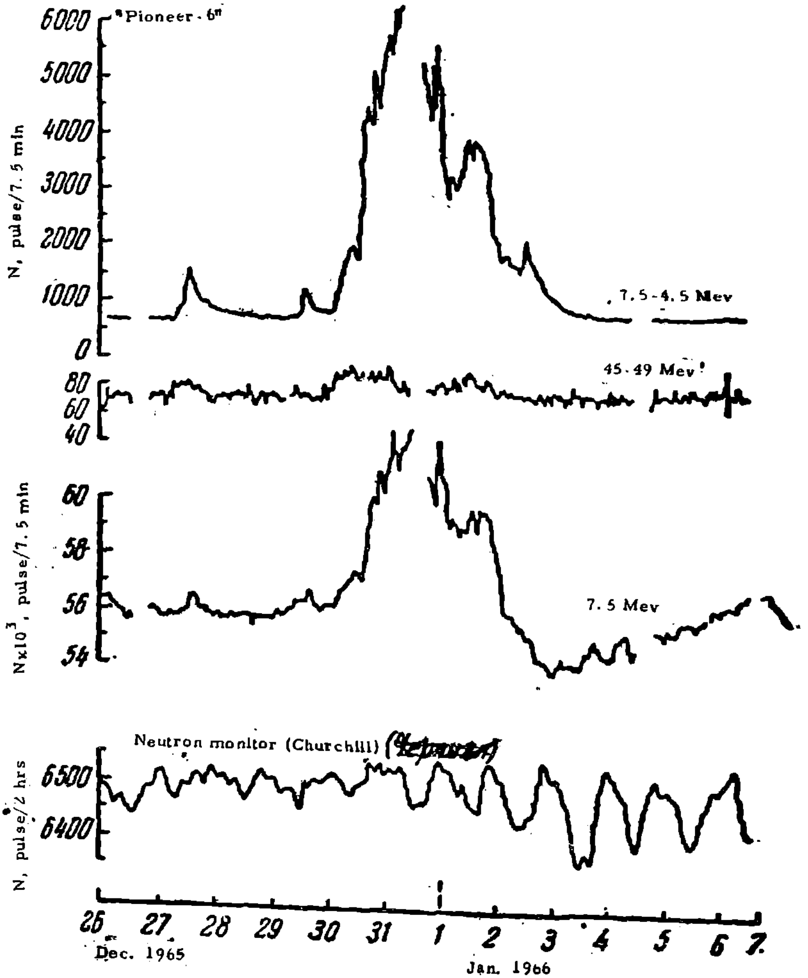

Fig. 13.1. Data of "Pioneer-6" and neutron monitor at Churchill for the period December 26, 1965 - January 5, 1966.

Data from neutron monitor at Churchill show that the interplanetary space was quiet during December 27-31, 1965. Daily variations were small and average daily values of counting rate were large. An exceptionally large daily variation was observed on December 31, 1965 which suggests a change in the conditions of the interplanetary space. Geomagnetic storms with sudden commencement were not observed during this period although during December 27-31, 1965, recurrent M-region was observed on the Sun.

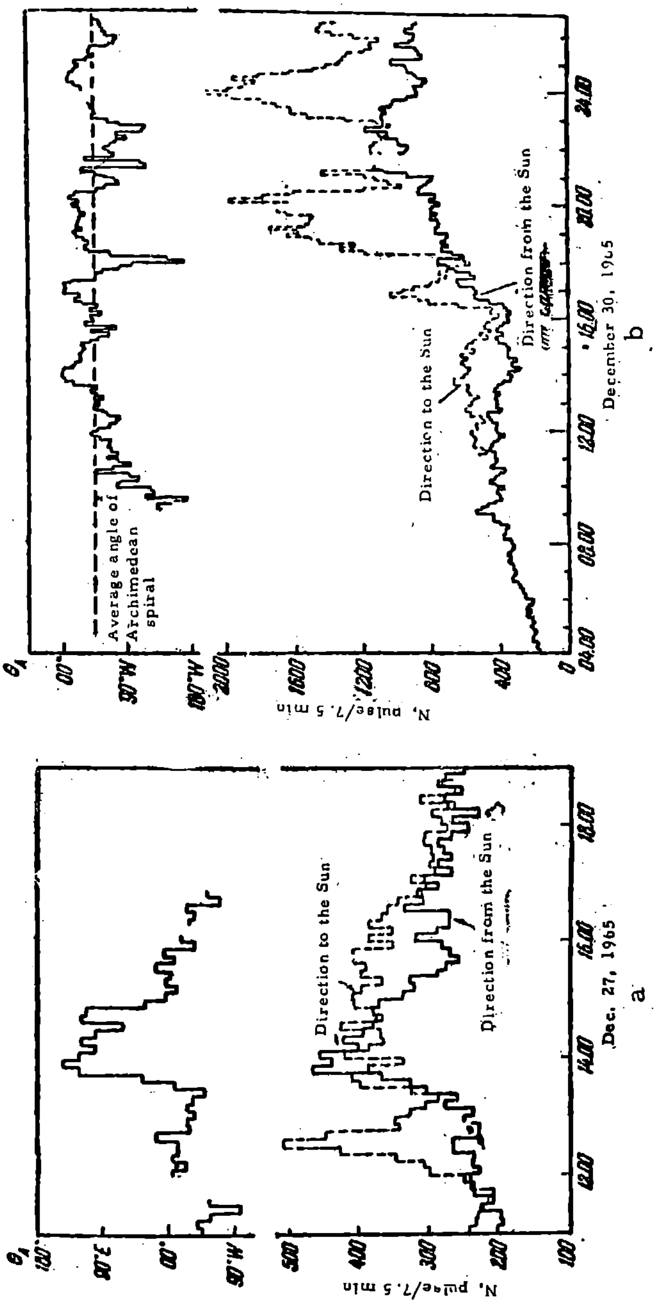

Fig. 13.2. Counting rate and direction of the anisotropy of the beam of low-energy particles:
a - December 27, 1965; b - December 30, 1965.

Counting rates of detectors, in specific directions and the azimuthal angle θ_A of the anisotropy of cosmic rays for the initial phase of December 27 and 30, 1965 flares, are shown in Fig. 13.2 (data are averaged for periods of 7.5 minutes). Angle θ_A corresponds to the direction (relative to the Earth-Sun line or "Pioneer-6" -Sun line) from which the detector records the maximum flux of cosmic rays in the given range of energies. Simplified model of the interplanetary magnetic field is shown in Fig. 13.3 in the form of the fibrous structure. Every fiber of diameter 3×10^6 km apparently represents a pencil of the tubes of force. Low-energy particles must move in this direction along the fibers.

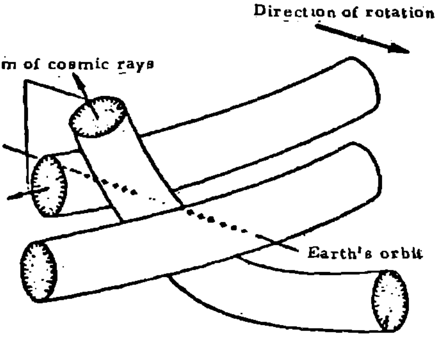

Fig. 13.3. Simplified model of fibrous structure of the interplanetary magnetic field.

Since coordinates of the source and time of emission of solar particles are known only approximately, it is very necessary to know the correct characteristics of their motion.

It was earlier shown that data on cosmic rays (McCracken [4]) and magnetic data (Ness et al. [13]) are, in general, in agreement with Parker's model [15] for the interplanetary magnetic field in the form of Archimedean spiral. In particular, if the characteristic dimensions of irregularities in the interplanetary field are larger than the cyclotron radius of a particle, the adiabatic invariance $\sin^2\theta/H$ must be satisfied where θ is the pitch angle of the moving particle.

In this case, as mentioned by McCracken [4], there must be collimation of particles. As a matter of fact, if it is assumed that the decrease in radial field with distance is proportional to r^{-2}, the first adiabatic invariant leads to the relation $r^2 \sin^2 \theta$ =const, i.e., particles at large distances must move strictly along the lines of force. For example, if the pitch angle of a particle θ =90° near the source (Sun), it will move at the Earth's orbit at an angle $\theta \approx 1^\circ$. It means that the isotropic beam of particles near the Sun reaches the Earth in the form of a well-collimated pencil, parallel to the lines of force at the Earth's orbit (Fig. 13.4). It can be shown that the times of flight, from the Sun to the Earth, of relativistic particles with pitch angles θ =0° and θ =90° differ by about 2 minutes.

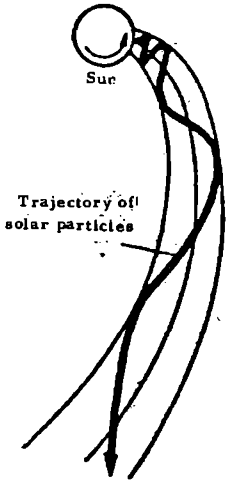

Fig. 13.4. Collimation of particles in the interplanetary space during their propagation from the Sun to the Earth.

If the lines of force of the field at the time of the flare connect the Earth and the active region responsible for the flare, there should be well-defined impact zones on the Earth. Obviously, every quasiradial field will have low pitch angles at the Earth's orbit while the actual change of field with distance will be insignificant. It should, however, be underlined that the resultant angular distributions of particles near the Earth will be defined by two competing processes: collimation of particles with respect to lines of force of the regular quasiradial field and their scattering at magnetic irregularities depending on the energy of particles, and distribution of irregularities according to their dimensions, intensity of field in them and the distance between them.

The value of H for particles, rotating about the lines of force of the magnetic field, decreases by about 10^4 times during their movement from the Sun to the Earth. Therefore, pitch angle of a particle near the Earth's orbit will small($< 1°$) and the beam of solar cosmic rays will be extremely anisotropic while the vector of the beam of particles from the Sun will be parallel to the lines of force of the magnetic field.

Irregularities in the interplanetary magnetic field with characteristic dimension comparable to the cyclotron radius of particles lead to scattering of cosmic rays and the disappearance of the anisotropy.

It was shown by Bartley et al. [III. 133] that the beam of particles, generated by the Sun and arriving at the Earth during December 29, 1965 and January 1, 1966, was extremely anisotropic. Direction of the maximum flux, which changed noticeably with time, was also determined for all intervals of time. In particular, during a certain period, maximum flux of particles was directed 90°-150° to the east of the Earth-Sun line. Such a direction cannot be explained on the basis of the simple theory of Archimedean spiral of the field.

McCracken and Ness [III. 134] studied the data corresponding to the period 1600-2400 UT December 29, 1965 when the satellite "Pioneer-6" was situated at a distance of 2.8×10^6 km from the Earth at an angle of 90° to the Earth-Sun line and towards east of the Sun. During this period, three events were recorded when the angle of anisotropy became more than 90° to the west of the Earth-Sun line. Results obtained at the same time from magnetic field are described in the work of Ness et al. [16]. A sudden change in the direction of the interplanetary magnetic field was detected from these data. Results on magnetic field and cosmic rays, obtained in [III 134] and [16] lead to the conclusion that the interplanetary field has a fibrous structure.

Relation between the direction of anisotropy of cosmic rays and azimuth of the vector of lines of force of the magnetic field is shown in Fig. 13.5. Each point is obtained by taking the average of observational data for every 7.5 minutes. High degree of correlation (0.877) is seen from which it follows that the direction of anisotropy of cosmic rays actually agrees well with the direction of the magnetic field (average regression coefficient is equal to 0.890).

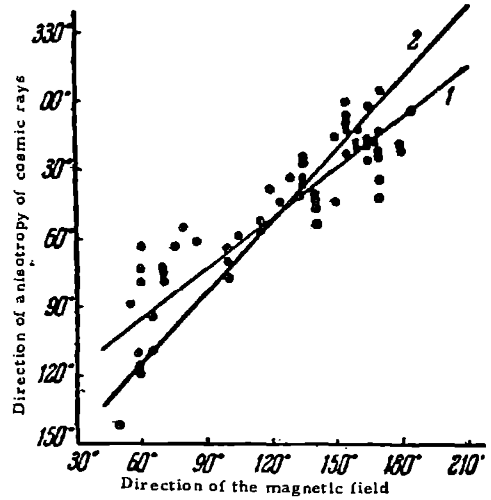

Fig. 13.5. Correlation between the direction of anisotropy of cosmic rays and the direction of lines of force of the interplanetary field from the data of 'Pioneer-6':
1 - correlation coefficient (0.877); 2 - regression coefficient (0.890).

Averaged data for every 7.5. minutes, showing the direction of anisotropy and magnetic field in the form of a vector diagram projected on the ecliptic plane are given in Fig. 13.6. The amplitude of anisotropy, calculated from its ratio to the average intensity of cosmic rays in the solar system, is characterized by the length of the arrow. It is seen that fluctuations of amplitude were observed sometimes but the anisotropy was always well-defined and it was always related to the field.

The period between 1750 and 1825 UT is of special interest when the field and vector of anisotropy were directed at an angle > 90° relative to the "Pioneer-6" -Sun line. In this case, the vector of anisotropy shows the direction along which motion should be towards the Sun in order to reach the region of the flare generating cosmic rays. It follows from this that there can be loops and bends, in addition to the fibrous structure of the field consisting of tubes of lines of force, in the form

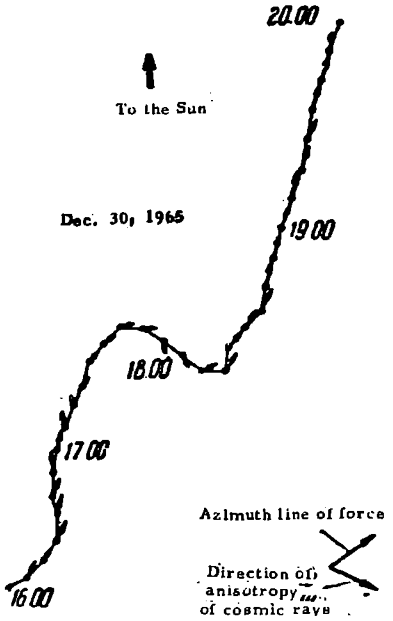

Fig. 13.6. Magnetic field and azimuth flux of cosmic rays from the data of "Pioneer-6" for the period 1600-2000 UT December 30, 1965.

of Archimedean spirals. It is schematically shown in Fig. 13.7. It is explained by the radial divergence of the lines of force in the interplanetary space.

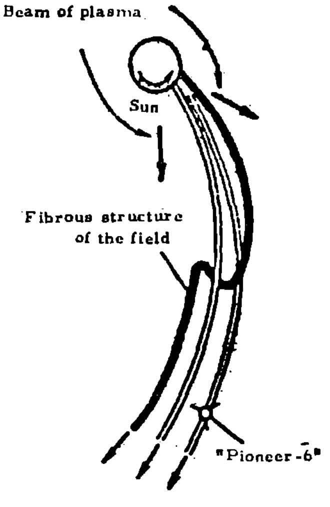

Fig. 13. 7. Schematic representation of the fibrous structure of interplanetary field.

Measurements by Strong et al. [130] with the satellites of the type "Vela" showed that parameters of the solar wind (velocity of plasma, direction of the beam, temperature, concentration, content of α-particles) change slowly within the fibers and relatively quickly at the boundary of the fibers. Width of the fibers is apparently of the order of a few million kilometers.

Measurements on the magnetic-field vector in the interplanetary space between the Earth and the Mars, taken by Siscoe et al. [131] with "Mariner-4", showed the presence of quick changes in the field and particularly, in its direction. Statistical analysis showed that duration of change in the field by a value $\gtrsim 4\gamma$ is apparently very small. During quiet periods, out of all the irregularities with duration $\lesssim$ 5min, about 50% had a duration $<$14 sec and 10% - $<$2 sec. During disturbances, this tendency is still more pronounced. Direction of field in the irregularities apparently changes in one plane and its intensity practically does not change. Thus, owing to rotation of the Sun, lines of force and whole of the structure in general rotates along with the Sun.

On the basis of Fig. 13.5, it can be said that scattering of cosmic rays in tubes with local bends did not at all differ from scattering in tubes with field in the form of the classical Archimedean spiral.

Results [III. 134] on cosmic rays and magnetic field are shown in Fig. 13.8 in a magnified scale for the period 1740-1840 UT December 30, 1965. It is seen that azimuthal direction of the magnetic field and the direction of anisotropy changed suddenly at 1809 UT. From the model of fibrous structure of the interplanetary field, it follows that these changes correspond to transition from one fiber to another. The time during which the anisotropy changed (1811-1817 UT) corresponds to the spatial shift by about one cyclotron radius for a proton with $\mathcal{E}_k$ = 13 Mev. Such a sudden change of anisotropy is possible only in an absolutely regular field. This fact as well as invariance of anisotropy before 1811 UT and after 1818 UT shows that in this case, cosmic rays moved from the Sun through a well-regulated field.

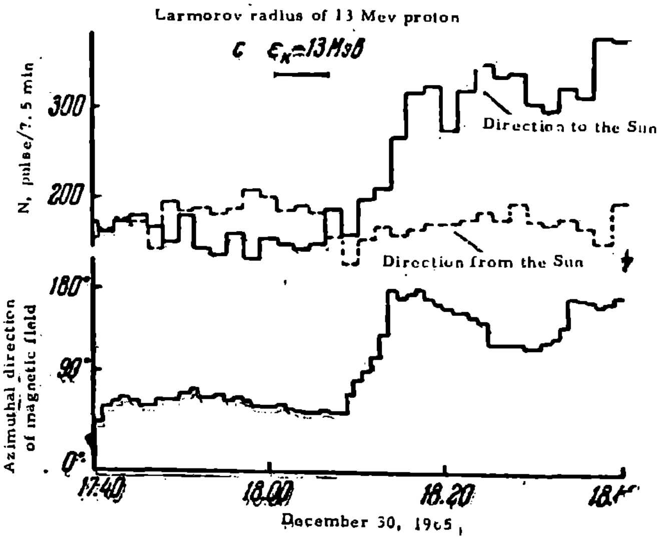

Fig. 13.8. Intensity of cosmic rays from two opposite directions and the direction of the interplanetary field during 1740-1840 UT on December 30, 1965.

Considering the effect observed at 1810 UT and other similar cases, it is possible to make an attempt to evaluate the longitudinal distribution of the corresponding fibers of the field near the Sun. Bartley et al. [III, 133] showed that injection of particles took place in regions differing in longitudes by $\lesssim 25°$. Since, during every transition from one fiber to another, each was rich in cosmic rays, McCracken and Ness [III, 134] arrived at the conclusion that a fiber is always related to regular field at points on the Sun's surface differing in longitudes by not more than 25°. Thus, fibrous structure of the field is apparently well regulated, i. e., the fibers retain their mutual location along the longitude in spite of the presence of loops and bends.

Thus, development of the investigations on cosmic space significantly explains and corrects the concepts on the interplanetary magnetic field and, in the long run, leads to the concept of magnetic trap of the solar system in which propagation of solar cosmic rays is defined by the regular field as well as by irregularities of the field (anisotropy of diffusion). In this case, relative role of regular and irregular parts of the field depends on the energy of particles. As will be seen in the subsequent Sections, discovery of the complicated structure of the interplanetary field does not at all reduce the importance of investigations on diffusion model. On the other hand, a study of the differences between this model and the experimental data gives valuable information on magnetic fields as well as on the processes of generation and exit of particles from the accelerating region.

13. 3. Motion of solar particles in irregular magnetic fields.

Let us first of all consider the simplest case -- diffusion of particles at magnetic irregularities. If dimensions of irregularities are denoted by ℓ and distance between them by d, the following two cases, as applicable to investigations on cosmic space, can be of interest: $\ell \ll d$ and $\ell \sim d$. Let us study them successively.

1) $\ell \ll d$. As density of magnetic irregularities in this case is $\sim d^3$ and the effective cross section of collision of a particle with irregularities $\sim \ell^2$, the mean free path L for collision will be $d^3 \ell^{-2}$. Let H_s be the average intensity of magnetic field in between them. Particles with charge Z_e, momentum p and radius of curvature $\rho = cp/ZeH_s < \ell$ will experience effective scattering. Their motion will be described by the diffusion equation with diffusion coefficient $\varkappa = \Lambda v/3$ where v is the velocity of particles and Λ is the average mean free path for diffusion, in this case, equal to the mean free path L before collision with irregularities. If $\rho < \ell$, the particle during every collision with irregularity will deviate from the initial direction of motion by a small angle $\theta \sim \ell/\rho$ on the average. In this case, in order that the deviation may accumulate to an angle ~ 1, ν collisions are necessary and the deviation will be determined by the relation $1 \sim \sqrt{\nu}\,\theta$ applicable to multiple scattering. From this, $\nu \sim \rho^2/\ell^2$. Therefore, for a significant change in the direction of motion of particles in the case of such multiple scattering, the time required will be $\nu/v\,L$ and the transport mean free path for scattering is $\Lambda \sim \nu L \sim d^3 \rho^2 \ell^{-4}$.

In the general case, with an accuracy of about 1 for the coefficient, it can be written

$$\Lambda \sim d^3 l^{-4}\left(1+\frac{\rho^2}{l^2}\right) = d^3 l^{-2}\left[1+\left(\frac{cp}{ZeH_s l}\right)^2\right]. \qquad (13.1)$$

It follows from (13.1) that for all particles with $cp/Ze \lesssim H_s\ell$ the value of Λ does not depend on the momentum of particles, whereas at $cp/Ze > H_s\ell$, $\Lambda \sim p^2$.

2) $\ell \sim d$. In this case, $L \sim \ell$. On reasoning ina similar way as above, we get

$$\Lambda \sim l\left[1+\left(\frac{cp}{ZeH_s l}\right)^2\right], \tag{13.2}$$

which conicides with (13.1) at $d \sim \ell$.

Let us now consider a more general case when there is a group of irregularities of magnetic field with dimensions from ℓ_1 to ℓ_2 and having distribution of density $f(\ell)$. In this case, mean free path before collision will be $f^{-1}(\ell)\,\ell^{-2}$. Let the intensity of field at the irregularities be the same on the average and equal to H_s. Then, mean free path for diffusion at irregularities of dimension ℓ will be

$$\Lambda(l) \sim f^{-1}(l)\,l^{-2}\left[1+\left(\frac{cp}{ZeH_s l}\right)^2\right]. \tag{13.3}$$

The effective mean free path for diffusion at all the irregularities will be determined by the relation

$$\frac{1}{\Lambda_{\mathrm{eff}}} = \frac{1}{l_2-l_1}\int_{l_1}^{l_2}\frac{dl}{\Lambda(l)}, \tag{13.4}$$

where $\Lambda(\ell)$ corresponds to equation (13.3).

Let us consider the special case when the irregularities are situated at large distance d from each other and their density does not depend on ℓ. In this case, $f(\ell) \sim d^{-3}$ and according to (13.3) and (13.4), we get

$$\Lambda_{\mathrm{eff}} = d^3(l_2-l_1)\left[\int_{l_1}^{l_2}\frac{l^4\,dl}{l^2+\rho^2}\right] =$$

$$= d^3(l_2-l_1)\left[\frac{1}{3}(l_2^3-l_1^3)-\rho^2(l_2-l_1)+\rho^3\,\mathrm{arctg}\,\frac{l_2-l_1}{\rho\left(1+\frac{l_1 l_2}{\rho^2}\right)}\right] \tag{13.5}$$

From Fig. 13.9, a, where dependence of Λ_{eff} on ρ is shown. it is obvious that, if $l_1 \ll l_2$, for $\rho \lesssim l_2$, $\Lambda_{eff} \sim 3d^3/l^2$ but at $\rho \gg l_2$ the value of Λ_{eff} increases rapidly in proportion of ρ^2 (curve 1). If $l_1 \sim l_2$, the relation (13.5) changes into (13.1) and Λ_{eff} is found to be considerably less (about half) (curve 4) but at $\rho \sim l_2$, it rapidly increases just like ρ^2.

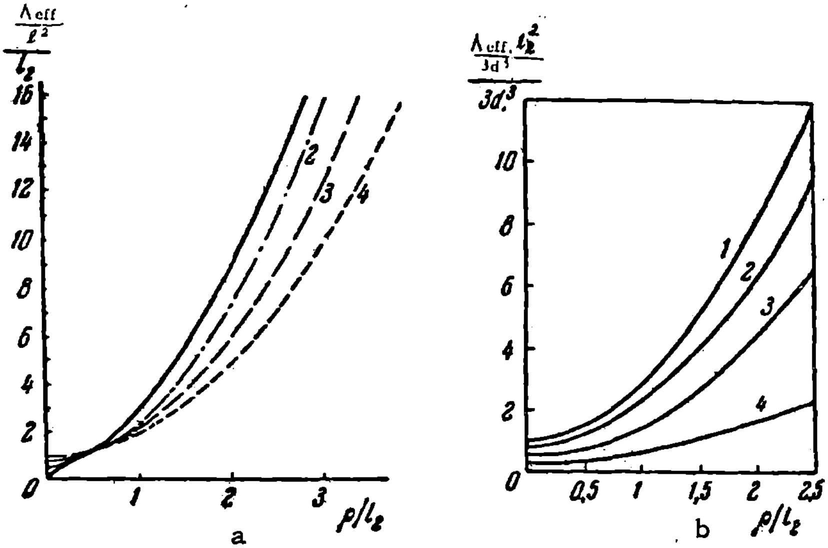

Fig. 13.9. Dependence of transport mean free path on momentum of the particles for two cases: a) irregularities of the field are situated at large distances from each other and their density does not depend on dimensions; b) distribution of irregularities is given by the relation (13.6).

1 - for $l_1/l_2 = 0$; 2 - $l_1/l_2 = 0.2$; 3 - $l_1/l_2 = 0.5$; 4 - $l_1/l_2 = 1$.

Let us now consider another case which corresponds to the well-developed turbulent medium with minimum dimensions of irregularities l_1 and maximum l_2. In this case,

$$f(l) = \begin{cases} l^{-3}, & \text{if} \quad l_1 \leqslant l \leqslant l_2, \\ 0, & \text{if} \quad l < l_1 \text{ or } l > l_2. \end{cases} \tag{13.6}$$

Putting (13.6) and (13.3) in (13.4), we get

$$\Lambda_{eff} = \left[\frac{1}{l_2 - l_1}\int_{l_1}^{l_2} \frac{l\,dl}{\rho^2 + l^2}\right]^{-1} = \frac{2(l_2 - l_1)}{\ln\dfrac{l_2^2 + \rho^2}{l_1^2 + \rho^2}}. \tag{13.7}$$

It is seen from (13.7) (Fig. 13.9, b) that irregularities for which $\ell \sim \rho$ are the most effective elements for scattering of particles. This important result can also be obtained from the following simple arguments.

Let us consider motion of particles whose radius of curvature in the field H_s is ρ. Scattering at irregularities for which $\rho \sim \ell$ will be defined by the mean free path $\Lambda_1 \sim \rho$. At the same time, scattering at irregularities of dimension $\ell << \rho$ will be determined by $\Lambda_3 \sim (\rho/\ell)^2 \cancel{\ell} = \rho(\rho/\ell) >> \Lambda_1$ i.e. the mean free path $\Lambda_3 \sim (\rho/\ell)\ell^2 = \rho(\rho/\ell) >> \Lambda_1$ i.e., in both the latter cases, scattering is considerably less effective and it can be neglected as compared to scattering at irregularities with $\ell \sim \rho$. If there is a group of irregularities with dimensions in the range $\ell_1 - \ell_2$ the diffusion mean free path, according to these simple arguments, will be

$$\Lambda_{\text{eff}} \sim \begin{cases} l_1, & \text{if} \quad cp \lesssim ZeH_s l_1, \\ \dfrac{cp}{ZeH_s}, & \text{if} \quad l_1 \lesssim \dfrac{cp}{ZeH_s} \lesssim l_2, \\ \left(\dfrac{cp}{ZeH_s l_2}\right)^2, & \text{if} \quad cp \gtrsim ZeH_s l_2, \end{cases} \tag{13.8}$$

which is well in accordance with the results shown in Fig. 13.9, b.

Let us now consider propagation of cosmic rays as a result of drift in irregular magnetic fields. In this case, trajectory of the particle will be a trochoid with radius of curvature $\rho = cp^{\perp}/ZeH$. The center of curvature will drift with a rate

$$u_{\text{dr}} = \frac{pv_{\perp}}{2H} \nabla_{\perp} H. \tag{13.9}$$

If irregular sections of the field completely fill the space and if each of them has dimensions ℓ with specific distribution $f(\ell)$, propagation of particles will have diffusion nature with mean free path Λ_{eff} determined by relations (13.7) and (13.8). The drift velocity u_{dr} at irregular sections of the field and not the velocity v of particles will be a part of the diffusion coefficient. Therefore, diffusion coefficient will have the form

$$\varkappa = \frac{\Lambda_{\text{eff}} u_{\text{dr}}}{3}. \tag{13.10}$$

i. e., this type of diffusion can be considered as propagation of particles with a velocity v but with mean free path

$$\Lambda_{dr}=\Lambda_{eff}\,\frac{u_{dr}}{v}\sim\frac{\Lambda_{eff}\rho}{2H}\,\nabla H. \qquad (13.11)$$

It is natural that only particles with $\rho << \ell$ will propagate in this way and therefore, every collision with an irregularity will be effective. If the irregularities do not fill the cosmic space but are situated at a distance d from each other, the particles will pass through irregularities during time $\Delta t_1 = \ell/u_{dr}$ and the space between the irregularities, during time $\Delta t_2 = d/v$ therefore, average effective rate of motion of particles will be

$$v_{eff}=\frac{d}{\frac{l}{u_{dr}}+\frac{d}{v}}=\frac{du_{dr}v}{lv+du_{dr}} \qquad (13.12)$$

and the diffusion coefficient

$$\varkappa=\frac{\Lambda_{eff}v_{eff}}{3}, \qquad (13.13)$$

where Λ_{eff} is determined from equations (13. 4) and (13. 5) and u_{eff} from equation (13. 12).

The situation, when there is a weak regular field of intensity H_0 in the space between irregularities, is also of great interest. In this case, motion of particles will represent anisotropic diffusion and the diffusion coefficient $\varkappa_\parallel$ along the field will be, to a first approximation, same as in the absence of the field ($\varkappa_\parallel = \varkappa$) and transverse to the field will be determined by the relation

$$\varkappa_\perp=\frac{\varkappa_\parallel}{1+\omega_0^2\tau^2}, \qquad (13.14)$$

where Larmorov frequency is given by

$$\omega_0=\frac{ZeH_0v}{cp} \qquad (13.15)$$

and the time between effective collisions of particles with irregularities of the field (when there is a significant change in the direction of motion) by

$$\tau\sim\frac{\Lambda_{eff}}{v_{eff}} \qquad (13.16)$$

In the last expression, Λ_{eff} and v_{eff} are determined from equations (13.4) and (13.12) respectively. If $\omega_0^2\tau^2 \ll 1$ there will be usual isotropic diffusion. If $\omega_0^2\tau^2 \gg 1$ it is necessary to consider anisotropy in propagation of particles. Of course, there can also be other, more complicated combinations of magnetic fields in the cosmic space. They can be investigated just like the cases considered above.

It is of interest to study scattering properties of magnetic fields having simples configurations H_s = const and $H_s \sim r^{-n}$ as applicable to diffusion process of the propagation of charged particles. For these scatterings, L.I. Dorman and Yu. G. Nosov [17] worked out the methods often used in the theory of atomic collisons: determination of differential effective cross section.

Let us consider two-dimensional case: charged particles move in a plane and vector H_s is perpendicular to this plane.

1) Let r be the radius of the circle in which H_s = const and $\rho = mvc/ZeH_s$. Then, the diffusion coefficient will be $\varkappa = 1/2\Lambda_{tr}v$ (there is 2 in the denominator since it is two-dimensional problem). In the simplest case, the transport mean free path is equal to the average mean free path Λ_s of a particle between collisions. This equality is true only if there is isotropy of scattering on collison. If the scattering is anisotropic, $\Lambda_{tr} \neq \Lambda_s$

$$\Lambda_{tr} = \frac{\Lambda_s}{1-\overline{\cos\theta}} = \frac{1}{N\sigma(1-\overline{\cos\theta})}, \tag{13.17}$$

where $N = 1/d^2$ is the number of scattering particles per unit area, d is the average distance between irregularities, θ is the scattering angle and σ is the scattering cross section which for two-dimensional case has the dimensions of length.

Let us introduce the parameter $\alpha = \rho/r$. Then, at $0 < \alpha < 1$, we get $\Lambda_{tr} = \Lambda_s = d^2/2r$ and $\varkappa = vd^2/4r$; at $1 < \alpha < \infty$ we have

$$\Lambda = \alpha^2\Lambda_s = \frac{d^2}{2r^3}\left(\frac{mvc}{ZeH}\right)^2, \tag{13.18}$$

$$\varkappa = \frac{vd^2}{4r^3}\left(\frac{mvc}{ZeH}\right)^2. \tag{13.19}$$

For ultrarelativistic particles, $v \to c$ and $mvc \to \mathcal{E}$ where $\mathcal{E}$ is the total energy of a particle. From this, we get

$$\varkappa = \frac{cd^2}{4r^3}\left(\frac{\varepsilon}{ZeH_s}\right)^2. \tag{13.20}$$

Scattering of particles, having different energies, by fields of the type H_s = const. is shown in Fig. 13.10. Vector of the intensity of magnetic field H_s, perpendicular to the plane of propagation of charged particles, can have two directions differing by an angle π. In the case of large values of d, diffusion will take place only if the frequency of encountering the magnetic fields having both the possible directions of H_s is the same. If there are magnetic fields of only one direction, the charged particles, deviating after every collision in the same direction, will not be able to come out of the limited space.

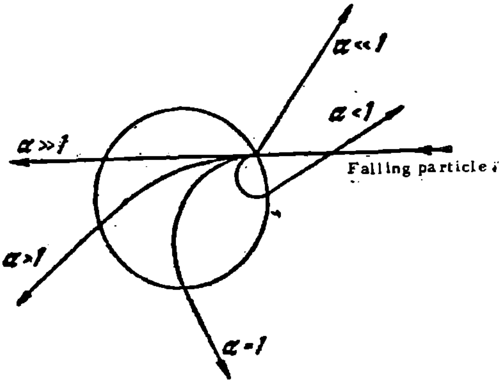

Fig. 13.10. Scattering of particles of different energies by irregularities of the type H_S = const [17].

2) Let $H_s = M/r^n$. Let us use the unit of length $\ell = (eM/mvc)^{1/(n-1)}$. After simple computations, we get

$$\varkappa = \frac{d^2 v}{2\sigma(1-\overrightarrow{\cos}\,\theta)} \sqrt[n-1]{\frac{mvc}{eM}}. \tag{13.21}$$

At $n = 1$, the parameter ℓ loses its significance as a unit of length. Consequently, fields $H_s = M/r^n$ cannot scatter charged particles at any value of n. Obviously, a particle cannot come out of the field $H_s = M/r^n$ at $n < 1$. In this case, centrifugal force $mv^2/r \sim 1/r$ decreases with distance more rapidly than H_s. Trapping and focussing of electrons by fields $H_s = M/r^n$ at $n < 1$ is used in betatrons.

If $n > 1$, the centrifugal force decreases with distance more slowly than H_s and the particle can go to infinity. Consequently, particles can be scattered by fields $H_s = M/r^n$ only at $n > 1$. At $n \simeq 3$, the magnetic field $H_s = M/r^3$ which corresponds to the distribution of field in the equatorial plane of the magnetic dipole. The unit of length ℓ takes the form $\ell = \sqrt{eM/mvc}$. Now M has the significance as that of magnetic moment of the dipole. If M is equal to the magnetic moment of the Earth, ℓ is sometimes called as "stormer" (see Section 7).

In the case of dipole field, we finally get

$$\varkappa = (0{,}18 \pm 0{,}02)\, d^2 v \sqrt{mvc/eM}. \tag{13.22}$$

For ultrarelativistic particles, (13.22) takes the form

$$\varkappa = (0{,}18 \pm 0{,}02)\, d^2 c = \sqrt{e/eM}. \tag{13.23}$$

Thus, if the irregular field is H = const in a circle of radius r, from formulas (13.19) and (13.20), we get the dependence $\Lambda \sim R^2$ for relativistic as well as nonrelativistic particles. If $M_r \sim 1/r^3$ (dipole field), from equations (13.22) and (13.23), we get $\Lambda \sim R^{1/2}$.

Motion of energetic particles in the interplanetary space is controlled by large-scale magnetic fields along with their scattering by small-scale irregularities. If $\varrho > \ell$, scattering is at small angles and if $\varrho \sim \ell$, the scattering takes place at large angles.

Earlier, this problem was studied by Parker [18] with the assumption of "thin" and "thick" scattering centers, scattering at which was considered to be partial if $\varrho \gg \ell$ and complete if $\varrho < \ell$. For high-energy particles ($\varrho > \ell$), such a model is probably fully satisfactory while at low energies ($\varrho < \ell$), it is necessary to apply the model of guiding center when the particles move through irregularities along the lines of force. In this case, the particles either undergo mirror reflection at some point of the irregularity does not significantly change during collision with a particle). The model of "thick" scattering center includes a wrong assumption about complete scattering at low energies. Actually, maximum scattering is observed at an intermediate energy when $\varrho \sim \ell$ which approximately corresponds to resonance between variations of the magnetic field and cyclotron frequency of the particle.

By this time, detailed observational data have been obtained on the propagation of energetic particles in the interplanetary space (see Chapters I and III). Therefore, it becomes necessary to describe scattering of particles at magnetic irregularities in more detail than is possible from the models of "thick" and "thin" scattering centers. To this end, Parker [19] studied the problem of a particle of mass m, charge q and velocity v moving in a magnetic field of uniform intensity Hs in x-direction and it was assumed that the magnetic field has only one irregularity of the type

$$F(x)=a\Phi\left(\frac{x}{b}\right) \tag{13.24}$$

or

$$F(x)=a\exp\left(-\frac{x^2}{b^2}\right), \tag{13.25}$$

where a is the amplitude, b is the characteristic length of the irregularity (Fig. 13.11) and Φ is the integral of probabilities.

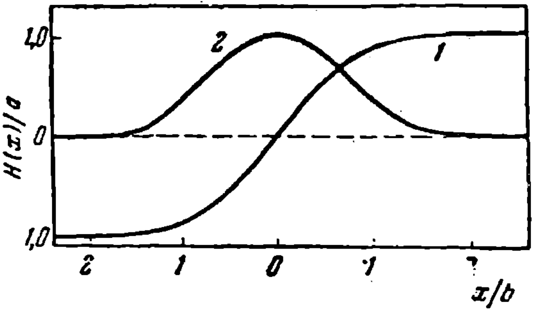

Fig. 13.11. Distribution of a field of two irregularities described by equations (13.24) and (13.25) (curve 1 and 2 respectively).

As shown in [14], the scattered velocity component, perpendicular to the field, is determined from the relations

$$\frac{\Delta v_\perp}{v_\parallel}=2\,\frac{a}{b}\cdot\frac{b}{\rho}\exp\left(-\frac{b^2}{4\rho^2}\right), \tag{13.26}$$

$$\frac{\Delta v_\perp}{v_\parallel}=\pi^{1/2}\,\frac{a}{b}\cdot\frac{b^2}{\rho^2}\exp\left(-\frac{b^2}{4\rho^2}\right). \tag{13.27}$$

The functions are shown in Fig. 13.12

It is seen that for fixed values of a and b, the scattering amplitude $\Delta v_\perp / v_\parallel$ tends to zero as ρ becomes very large or

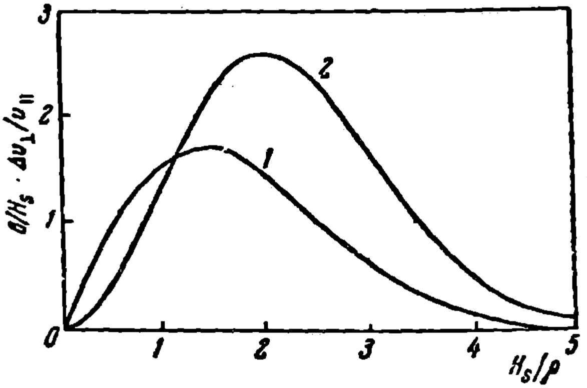

Fig. 13.12. Amplitude of scattering $\Delta v_\perp/v_\parallel$ at irregularities of the type (13.24) and (13.25), obtained from the relations (13.26) and (13.27) (curves 1 and 2 respectively).

very small. The scattering is maximum at $\rho = b/2^{1/2}$ and $\rho = b/2$ where $\Delta v_\perp/v_\parallel$ has the values of 1.72 a/b and 2.58 a/b respectively. Ratio of scattering amplitudes, determined from (13.26) and (13.27) is equal to $(2/\pi^{1/2})\rho^{1/2}$ which is less than one at low energies although, as a matter of fact, in each extreme case, scattering is low as compared to the maximum near the point $\rho/b = 1$ where (13.26) and (13.27) are comparable.

Considering irregularities in field distribution of the type

$$F(x) = a\frac{x}{b}\exp\left(-\frac{x^2}{b^2}\right), \tag{13.28}$$

$$F(x) = a\sin\frac{x}{b}\exp\left(-\frac{x^2}{L^2}\right), \tag{13.29}$$

Parker [19] derived the following two expressions for $\Delta v_\perp/v_\parallel$

$$\frac{\Delta v_\perp}{v_\parallel} = \frac{\pi^{1/2}}{2}\cdot\frac{a}{b}\cdot\frac{b^3}{\rho^3}\exp\left(-\frac{b^2}{4\rho^2}\right), \tag{13.30}$$

$$\frac{\Delta v_\perp}{v_\parallel} = \pi^{1/2}\frac{aL}{\rho^2}\operatorname{sh}\left(\frac{L^2}{2\rho b}\right)\exp\left[-\frac{L^2}{4}\left(\frac{1}{\rho^2}+\frac{1}{b^2}\right)\right]\sim$$

$$\sim\pi^{1/2}\frac{aL}{\rho^2}\exp\left[-\frac{L^2}{4}\left(\frac{1}{\rho}-\frac{1}{b}\right)^2\right] \tag{13.31}$$

at $L >> \rho$, b

These expressions show that increase in the number of regular fluctuations of field can noticeably reduce pure scattering at $\mathcal{S} > \ell$. Obviously, for the theory of scattering of high-energy particles, it is important to solve the problem as to whether the irregularities should be considered as different and independent disturbances of the field or every such distrubance in one direction is accompanied by an extremely similar convexity in the opposite direction.

These examples serve as an illustration of the nature of scattering of a charged particle by irregularities in a large-scale field. On reducing the rigidity of particles, scattering goes on intensifying till it becomes maximum at the time of resonance between the cyclotron frequency and rate of change of field acting on the moving particle. As mentioned earlier, at low energies, scattering decreases to zero and therefore, motion of particles can be described on the basis of the model of guiding center. The particle in this case either undergoes mirror reflection or passes through the irregularity without changing the pitch angle. These facts should be kept in view while interpreting observational data on the propagation of energetic particles by taking into account the irregularity spectrum measured by Coleman[20, 21] at the end of 1962 on "Mariner - 2".

For the expressions obtained in [19] to be true, it is necessary that $\Delta v_{\perp}/v_{\parallel} \ll 1$. This requirement is authomatically satisfied for large and small values of b/ℓ. However, for its applicability at all values of b/ℓ, it is necessary that the condition $(\Delta v_{\perp}/v_{\parallel}) \ll 1$ is fulfilled. From this follows the requirements $a \ll b$, i.e., the irregularity should have small "inclination" and its length should be more than its amplitude or $a \ll 0.2b$. Obviously, it automatically leads to the requirements that length of the path, measured along the lines of force, may not increase too much due to the effect of irregularity (i.e., due to twisting of the line of force). It also signifies that compression of the lines of force in the irregularity is not large and therefore, all the particles with pitch angles $\theta \leq 1$ radian pass through the irregularity more or less freely without mirror reflection.

Motion of charged particles in the interplanetary space is considered in a number of works of Roelof [22-26]. For studying the propagation of low-energy solar protons of energy 1-10 Mev, it is assumed in [22] that the charged particles will diffuse through the magnetic fields which are so irregular that approximation of guiding center is not applicable for describing the motion of a particle. For studying the transfer of particles in these fields, the equation of motion $\partial v/\partial t = v \times \omega$ (ω-gyrofrequency equal to ZeH/mc and v-velocity of the particle) is solved, in which v and ω are taken as stochastic variables. Magnetic field is the sum of average field H_0 and fluctuating field h, the average value of the autocorrelational function of which is equal to zero. The field h can change with time as well as in space. Such consideration is applicable only if $\partial h/\partial t$ does not give rise to significant induced electric fields. It was found that distribution function for v satisfies the two-dimensional equation of Fokker-Planck (on a sphere of radius v in the space of velocities). The process is characterized by three parameters: 1) average field H_0; 2) mean square component of fluctuating field; 3) space parameter of correlation l for fluctuating field. It has further been shown that the particles actually diffuse and at $h^2 >> H_0^2$, diffusion is in three directions while at $H_0 \gg h$ it is mainly in one direction (along H_0).

Solution of Fokker-Planck equation of motion of charged particles in an average magnetic field $\bar{B}_0$ with superimposed isotropic arbitrary field $\bar{B}$ shows [23] that distribution of velocities is asymptotic with characteristic time of relaxation $\tau = 2vq/\pi (mc)^2 P(k_0)$. Here v, q and m are the velocity, charge and relativistic mass of the particle respectively, c is the velocity of light and $P(k_0)$ is the spectral energy density of any component of the arbitrary field B defined by the wave number $k_0 = qB_0/mcv$. For the case $B_0^2 \gg B^2$ corresponding to the interplanetary magnetic field, it can be assumed that the average field B_0 changes slowly in space if the characteristic length $L = B_0^2/\bar{B}_0 \Delta B_0$ is slightly more than the "relaxation length" of velocity $v\tau$. Asymptotic distribution of velocities, in this case, has the form $(\zeta/2 \operatorname{sh}\zeta) \exp(\zeta\mu)$ where $\zeta = v\tau/2L$ and μ is the cosine of the pitch angle of the particle, measured from the direction of the decreasing field. This process of distribution of velocities leads to the diffusion equation with diffusion coefficients $\varkappa_1 = v^2\tau/6$ along the average field and $\varkappa_2 \approx (\Omega_0\tau)^{-2}\varkappa_1$ perpendicular to the field. Average drift velocity along the field is equal $\bar{\mu}v$ where

$\bar{\mu}$ = Arcth ξ. Comparison of diffusion equation with observation data on solar cosmic rays gives $\varkappa_1 \sim 10^{21}$ cm^2/sec. Near the Earth's orbit, it corresponds to $\tau \sim 10^2$ sec and therefore, $\varkappa_1 >> \varkappa_2$ and $\xi \sim 10^{-1}$. Thus, propagation of solar protons apparently corresponds to monometric diffusion along the lines of force with slight anisotropic distribution of particles along pitch angles. Externally, drift will give rise to intensification of the decrease in the particle flux at the end of the event. Spectral energy densities obtained on the basis of diffusion coefficient for flares, starting from 1956, are about one order less than those from spectrum of irregularities obtained by Coleman [20] on "Mariner-2" and are in agreement with the form for Larmorov frequencies of protons with $\mathcal{E}_k$ = 20-2500 Mev.

Propagation of charged particles in the interplanetary magnetic field is studied in [24] with the help of statistical methods and the theory of adiabatic motion. The guiding center of particles moves along the smoothened average field B and small, arbitrary spatial changes of field b change to irregular distribution of pitch angles with characteristic relaxation time $\tau = m^2c^2v/2q\,b^2\,l$ where m, v and q are the mass, velocity and charge of the particle respectively, c is the velocity of light, b^2 is the mean square amplitude of disturbance and l is the length of correlation of field disturbances. If B is uniform, diffusion takes place along lines of force with mean free path $\Lambda = v\tau$, i.e., Λ is proportional to v^2. Since B decreases on increasing the distance from the Sun, rotation of the direction of motion of particles appears to be less probable although small ($\sim$ 10%) local increases in the field B at a distance of r from each other lead to such rotation of the direction for particles having large pitch angles. If $v\tau < r$ irregularities can be observed at $\Lambda \sim r$, i.e., Λ is proportional to v_0. Electron with $\mathcal{E}_k \sim 40$kev and protons with $\mathcal{E}_k \sim 100$ Mev apparently satisfy the conditions of this diffusion with mean free path Λ not depending on velocity. At the same time, their velocities are comparable and therefore, they should have diffusion coefficients of the same order which is in agreement with the results of observations. Anisotropy of beams of energetic solar particles, observed by measuring 7.5-45 Mev protons on "Pioneer-6" and 45 kev electrons on "IMP-3", is the source of information on local properties of the interplanetary magnetic field and on propagation of particles in this field.

It was found in [25] that local diffusion coefficients along and transverse to the lines of field are $\varkappa_{\parallel} \approx v^2 \tau/6$ and $\varkappa_{\perp} \approx (\Omega \tau)^{-2} v_{\parallel}$ and therefore, propagation of particles at a distance of 1 a. u. is highly collimated along the lines of field. In the regions where the line has irregular distortion to distances $\gtrsim v\tau$, pitch angles (ψ) have the distribution $\sim$ (2 shk) exp(k cos ψ) where $k = v\tau/2L$ (L is the characteristic dimension of mean field $B^2{}_o/B_o \nabla B_o$). Thus, anisotropy of the particles gives information (through k) on the statistical properties of local field and parameters of propagation of particles even if the observed phenomenon does not have the nature of simple diffusion. Preliminary comparison with the data of "Pioneer-6" at corresponding moments of time is well in agreement at $k \sim 15\%$ from where $\varkappa_{\parallel} \sim 10^{21}$-$10^{22}$ cm^2/sec for protons with $\mathcal{E}_k = 7.5$-45 Mev. "IMP-3" data on electrons have more complicated nature. Apparently, arbitrary distortions along the line of force for the wave number, corresponding to electrons with $\mathcal{E}_k = 45$ Mev, can be "discontinuous" within the limits of the scale.

Results, obtained on solving the problem of motion of charged particles in the interplanetary magnetic field [24, 25] are compared in [26] with the data on spatial power spectrum of the interplanetary magnetic field by assuming that time variations of magnetic field, recorded on a satellite, are related only to the three-dimensional irregularities of the field. In this case, values of experimentally measured diffusion coefficients for particles of different energy were used. It is pointed out that space variations, corresponding to wave-length $\sim$ 0.1 a.u., represent the characteristic feature of the interplanetary magnetic field.

According to Wibberenz [27], drift can play the same role in propagation of particles as scattering if the particles move transverse to the magnetic field and it is possibly more effective in certain configurations of magnetic fields. Dependence on velocity and rigidity is insignificant in both the cases. The possible effect of drift on the value of p : α ratio is discussed in [27] on the basis of observations near the Earth at different stages of cosmic-ray flares. This ratio at a constant energy per nucleon practically does not change with time if the dependence of Λ on rigidity is taken into account as was done in Krimigis' model of isotropic diffusion [28] (also see Krimigis and Van Allen [29]).

Data on actual interplanetary field are of great interest for the theory of propagation of cosmic rays in the solar system. In this connection, let us consider basic results of the work of Coleman [20] in which the properties of variations of interplanetary magnetic field observed with the help of the magnetometer on "Mariner-2" during August 20 -- November 15, 1962 are described. In the spherical system of coordinates with center on the Sun and polar axis coinciding with the axis of rotation of the Sun, interplanetary field is described by the components B_r, B_θ and B_φ. It was shown that amplitude distributions of these components, taken during the periods with constant polarity of field, are more or less similar to the Gauss distributions. Width of these distributions is equal to 5.8; 10.0 and 10.0 gamma^2 for B_r, B_θ and B_φ respectively. It should be underlined that width for radial component Br is considerably less than that for the two transverse components. Spectra of energy density are given for each of the three components in the frequency range of 1.35×10^{-5}-1.35×10^{-2} Hz. Comparison of the spectra shows that variations of radial components are less than those for the components B_θ and B_φ in the whole range of frequencies and the ratios of energy densities Br, B_θ and B_φ practically do not depend on frequency. Energy density in the spectrum is a sharply decreasing function of frequency while the spectrum has the form $dh^2/df \sim f^{-1}$-f^{-2} in the frequency range of $(1.16$-$5.8) \times 10^{-3}$ Hz.

Fig. 13.13 shows the spectrum of energy density for B_φ-component of the interplanetary field which is perpendicular to the Sun-"Mariner-2" line and lies in the plane of solar equator. Results obtained for different periods and from different methods of machine processing of primary data are shown by different symbols. In October 1962, average intensity of interplanetary field was about 5γ while the velocity of solar wind was approximately equal to 400 km/sec. In the frequency range of 3×10^{-4}--3×10^{-5} Hz the spectrum is well described by the function which has a tendency to increase the inclination at $f \gtrsim 5 \times 10^4$ Hz.

Recently, spectra of energy densities for different components of the interplanetary field were obtained by Siscoe et al. [30] from the magnetometer data of "Mariner-4" during the two-week quiet period in the end of 1964. In this case, spectrum of transverse component B_φ was also approximately proportional to

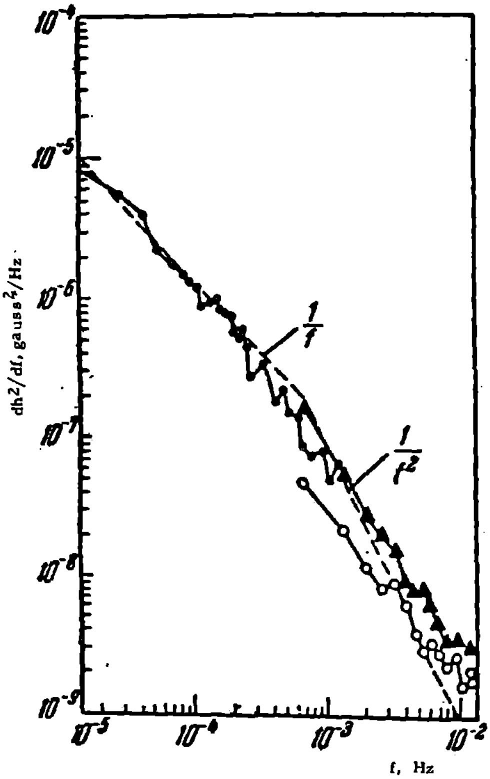

Fig. 13.13. Spectrum of energy density for B_φ - component of the interplanetary field' in October 1962.

f^{-1} at low frequencies with transition to steeper spectrum at $f \gtrsim 10^{-4}$ sec. The fact, that transition to steep spectrum in 1964 took place at a frequency lesser than in 1962, can be significant during analysis of modulation effects of particles of extremely low energies.

One of the latest works on the study of the motion of particles in the irregular field was carried out by Jokipii [31]. In[31], magnetic field is considered to be the superposition of a constant field B_0 and a small fluctuation component B_1 which is a uniform arbitrary function of coordinates with zero mean value. Fokker-Planck coefficients, describing evolution of distribution of particles according to pitch angles and coordinates, are correctly derived with the help of two-point correlational function for B_1 or with the help of Furier spectrum of the irregular field. It has been shown that time evolution of distribution depends on irregular field in two ways: 1) the particle is scattered by that irregularity which corresponds to resonance with the cyclotron frequency of the particle; 2) the particle accomplishes arbitrary circulation along the lines of force in the plane xy and moves along the z-axis. Jokipii [31] also finds diffusion approximation for Fokker-Planck equation and derives the tension for diffusion coefficient. Applying coefficients to the observed spectrum of energy density of different components of the interplanetary field in the form $\sim f^{-1}$ Jokipii [31] showed that diffusion coefficient for a particle of rigidity R and velocity v, moving along the mean magnetic field B_o, has the form $\varkappa_{\parallel} \sim B_o Rv$. It should be mentioned that calculation of $\varkappa_{\parallel}$ in [31], required the condition that change in B_o should be small for the length of transport mean free path $\Lambda \lesssim \varkappa_{\parallel}/v$ to be satisfied. For protons with $\mathcal{E}_k = 100$ Mev, the mean free path is $\Lambda \lesssim 10^{12}$ cm while the characteristic dimension of the field beyond the Earth's orbit is more than 1 a.u. $= 1.5 \times 10^{13}$ cm and therefore, the required condition is satisfied. As shown in [31], diffusion is extremely anisotropic: $x_{\parallel} >> \varkappa$. While studying different assumptions about the nature of scattering by magnetic irregularities, L.I. Dorman [32] also found that $\varkappa \sim R\nu$; however, his results were obtained without referring to the observed spectrum of irregularities.

Gloeckler and Jokipii [33] made an attempt to apply the results of theoretical estimate of Jokipii [32] to the observational data of Fan et al. [III. 133; 34] obtained with satellites "IMP-1", "IMP-2" and "IMP--3" during almost two years near the minimum solar activity (December 1963--September 1965). The ratio of the intensities of primary particles $\ln[I_2(t_2)/I_1(t_1)]$ as a function of RV was studied for different times during the given period. The value of $\ln(I_2/I_1)$ was found to be inversely proportional to Rv which was well in agreement with the estimate given in [31] for the real interplanetary field. Other types of dependences $\ln(I_2/I_1) \sim R^{-1}$ or $\ln(I_2/I_1) \sim \nu^{-1}$ do not satisfy the experimental data in the considered range of rigidities (0. 03-2. 0 Gv). It should be mentioned that experimental points obtained during 1964-65 have a tendency to arrange themselves slightly below the straight line $\ln(I_2/I_1) \sim 1/Rv$ at low energies. According to [33], it may be caused by the increase in the steepness of the spectrum of energy density obtained in the end of 1964, at frequencies $f \gtrsim 10^{-4}$ Hz which corresponds to cyclotron frequency of the particles with $R \lesssim 0.3$ Gv. Similar results on effects of modulation of cosmic rays were obtained by a number of other research workers (see references in [34]).

Thus, observations on cosmic rays are well in accordance with the modulation effects expected from the irregularity spectrum of the real interplanetary field [20, 30]. Although magnetic data are not sufficiently complete and the diffusion coefficient is deterimined only for the region near the Earth's orbit, it is clear that modulation is caused by magnetic irregularities carried by solar wind and that the motion of particles can be quantitatively described by the measured spectrum of irregularities.

The relation between diffusion coefficient of cosmic rays and the spectrum of irregularities of the interplanetary magnetic field is studied in the work of A. Z. Dolginov and I.N. Toptygin [35]. On the basis of the kinetic theory (see Section 16), the authors [35] got the following expression for mean free paths:

$$\Lambda_{\parallel} = \frac{\nu\rho^2}{\Lambda_{\perp}} = (2\nu + 4)\frac{A_\nu c^2 p^2}{e^2 \langle H_1^2 \rangle l}\left(\frac{eH_0 l}{cp}\right)^{\nu}.$$

where $A_\nu = \pi^{-1/2}\,\Gamma(\nu/2)\,\Gamma(3-\nu/2)\sin(\frac{\nu-1}{2}/\pi)$; is the index of irregularity spectrum of the field; H_0 is the regular field; $\langle H_1^2 \rangle$ is the mean square of the irregular field; l is the characteristic dimension of irregularities and $\Lambda_{\parallel}$ and $\Lambda_{\perp}$ are mean free paths along and transverse to the regular field respectively. Obviously, in the case of an extremely regular field ($\rho \ll l$), the mean free path of particles can depend on the momentum in different ways. It is explained by the fact that a particle of Larmorov radius ρ is effectively scattered at irregularities of dimensions $l \lesssim \rho$ whose specific weight is determined from the type of spectral function. Irregularities of magnetic fields, corresponding to the values of f from 10^{-2} to 10^{-4} Hz, observed in [20], are effective for scattering protons of Larmorov radius $\rho \approx v/f$. According to experimental data, putting $H_0 \gtrsim \langle H_1^2 \rangle$ and $\nu = 2$, the authors [35] arrive at the conclusion that the mean free path of such protons along the lines of force of the regular field does not depend on their momentum and is equal to $6 \times 10^5 - 10^6$ km.

On the other hand, if the regular field is weak, according to [35]

$$\Lambda_{\parallel} = \frac{\rho^2}{\Lambda_{\perp}} = 3c^2p^2\left[2e^2l\langle H_1^2(r)\rangle \int_0^{\infty} \Psi(x)\,dx\right]^{-1},$$

where $\Psi(x)$ is the correlation function, the components $\varkappa_{ij}$ are

$$\varkappa_{11} = \frac{v\Lambda_{\parallel}}{3}, \quad \varkappa_{22} = \varkappa_{33} = \frac{v\Lambda_{\perp}}{3}\,\frac{\rho^2}{\Lambda_{\perp}^2+\rho^2},$$

$$\varkappa_{23} = -\varkappa_{32} = \frac{v\rho}{3}\,\frac{\rho^2}{\Lambda_{\perp}^2+\rho^2},$$

and the remaining components of the diffusion tensor are equal to zero.

Very important results were obtained by Rinehart [36] who used the method of the theory of small disturbances for evaluating the effect of regular interplanetary field on the motion of protons. Diffusion coefficient is considered to be a tensor and the small parameter of the theory of disturbances is equal to the square of the ratio of the frequency of collision of protons with magnetic irregularities to the cyclotron frequency of protons in the regular field. The solutions of diffusion equation so derived on comparing with the experimental data on solar protons, facilitate evaluation of the relation between the parameters of the model under reference and apparently, offer a method for determining each of the parameters individually.

Reflection, trapping and propagation of energetic protons, associated with solar flares, in irregular magnetic fields of plasma clouds in the interplanetary space were analyzed with the help of statistical methods in the work of Waddell and McQuarrie [37]. The field was assumed to be nondirectional with the distribution, according to intensity, obtained by direct measurements. Distribution of protons in the cloud in space and with the passage of time was evaluated by the method of Monte-Carlo. The average time of existence of a proton in the cloud varies from a few seconds near the Sun to a few hours near the Earth. Consequently, protons easily penetrate the cloud in the corona over the flare and are carried by the cloud which contributes a lot to the intensity at the later stage of development of the phenomenon. Within the limits of the cloud, diffusion coefficient is inversely proportional to the mean square intensity of the field.

Using the approximation of guiding center, Sakurai [38] studied motion of charged particles in magnetic fields changing in space and with time. Drifting and mechanisms of acceleration of the particle are considered. Application of the results obtained to the mechanisms of acceleration of solar cosmic rays and to the motion of trapped particles in the external radiation belt is discussed in short.

Motion of solar cosmic rays in the interplanetary magnetic field was also studied by Bennet [39]. Bennet [39] considered the model of interplanetary magnetic field consisting of a collection of discrete, sharply marked fibers or tubes of lines of force. Longitudinal and transverse scales can be attributed to every fiber. If these scales are retained at all the points of fiber, the magnetic momentum of particles (first adiabatic invariant) is also retained. The fiber in this case becomes fluent for nonrelativistic solar protons while the pitch angle of particles systematically decreases with an increase in the heliocentral distance as a result of which the beam becomes anisotropic. It is shown that the transverse scale is an invariable internal property of the tube of lines of force. Longitudinal scale may be disturbed by the loops of magnetic field caused by magnetohydrodynamic shock waves from solar flares. Every discrete scattering center is considered as a virtual source of particles. Particles of very low rigidity will continue satisfying the corresponding scales and retain focusing while the rigid particles get diffused. Nature of the phenomenon, associated with propagation of particles of solar flares, significantly depends on heliocentral distance and number of magnetohydrodynamic shock waves coming in the path of the beam of energetic particles.

Rostami and Coleman [128] studied motion of charged particles in the magnetic field of solar wind depending upon time and coordinates. On the basis of the results of "Mariner-2", interplanetary field is represented as superposition of spiral and arbitrary (irregular) fields. Diffusion coefficients have been calculated for every point of the space. The field was averaged for parameters with the help of computers. As was assumed, tensor of diffusion was found to be anisotropic.

Spatial and energetic dependence of diffusion coefficient were determined which in the case of diffusion along the average field was found to be equal to 10^{20}-10^{21} cm^2, sec^{-1} (for 50-500 Mev protons at a distance of 1 a.u.); this value is less than most of the previously obtained values.

14. DIFFUSION MODEL OF THE PROPAGATION OF SOLAR COSMIC RAYS

Different aspects of diffusion model of propagation of solar particles and basic results on interplanetary field, spectra, duration of emission and other characteristics of the particles, obtained on the basis of this model, are described in this Section.

14.1 Applicability of diffusion approximation. In this approximation, motion of cosmic rays is considered similar to diffusion of molecules in a gas with velocity v equal to the velocity along the lines of force of the magnetic field, and effective mean free path Λ which characterizes configuration of the field (in the simplest case, Λ is the size of region with approximately uniform field). One of the possible objections to this model lies in the fact that cosmic particles must move strictly along certain lines of force in accordance with conservation of adiabatic invariant. However, even within the framework of the views on adiabatic movements, it is necessary to consider drift of particles related to nonuniformity of the field and leading to transition of particles from one line of force to another. Moreover, adiabatic consideration in general is not applicable to that case when the density of the energy of the cosmic rays becomes comparable to the density of the energy of the magnetic field. In this case, the field no more defines the movement of cosmic rays but the cosmic rays themselves, to a great extent, determine the configuration of the magnetic field. These two considerations provide a base to visualize inevitable stirring (isotropization) of cosmic rays which can approximately be described by diffusion equation [I.21]*.

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* *As shown by Parker [I.61], there can be two mechanisms of stirring of particles in the interplanetary space: I - diffusion of fast particles in the passive scattering medium; II - diffusion due to movement of magnetohydrodynamic waves (the medium is active but the particles passive). The*

In the recent past, a new approach was suggested to the problem of isotropization of cosmic rays based on plasma effects. V. N. Tsytovich [40] considered two mechanisms of isotropization:

1) beam unstability of cosmic rays;
2) their scattering at turbulent fluctuations of plasma.

It was shown that, at the initial stage of development of beam unstability, there appear nonlinear effects of interaction of generated vibrations which, in the case of anisotropic relativistic particles, lead to liquidation of unstability and to discontinuance of isotropization process at very low values of energy passed on to plasma fluctuations by cosmic rays. However, in the presence of ion beams, in plasma, having average velocity more than or of the order of thermal velocity of ions in plasma, the nonlinear effects, on the contrary, facilitate isotropization. On the other hand, isotropization of cosmic rays due to scattering at high-frequency turbulent fluctuations of plasma or at hydrodynamic fluctuations, excited by some sources is very effective. Applicability of these effects considered by V. N. Tsytovich [40] to solar cosmic rays in the interplanetary plasma has not been studied up to this time. Apparently, there arise certain difficulties connected with the short-lived anisodropy of cosmic-ray flares.

Thus, sufficiently high degree of irregularity of interplanetary magnetic field is necessary for applying the diffusion approximation. Without referring to the causes of the origin of magnetic irregularities, it should be mentioned that their existence in the interplanetary space is indicated by such experimental facts as isotropy of the beam of solar particles near the Earth some time after the commencement of the flare and decrease in their intensity approximately according to the law $\sim t^{-3/2}$ which corresponds to the case of three-dimensional isotropic diffusion, widening of the image of the source of solar cosmic rays, displacement of shock zones for solar

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second mechanism is apparently more effective in higher regular fields (local fields on the Sun, geomagnetic field, etc.) while the first mechanism is probably more effective in the interplanetary space where the field is weak and irregular [21, 30] and the velocity of magnetohydrodynamic waves is small.

particles with simultaneous widening (arrival of particles in the prohibited zones), delay in the arrival of low-energy particles as well as direct measurements (see Section 13).

Requirement of independence of solar particles during their motion in the interplanetary as well as geomagnetic fields is of no less importance. Satisfaction of this requirement for interplanetary space does not apparently lead to any doubts if the weak intensity of interplanetary fields (10^{-3}-10^{-5} gauss) and low concentration of solar cosmic rays ($\sim 10^{-8}$ cm^{-3} for protons with $\mathcal{E}_k \sim 100$ Mev, according to Obayashi and Hakura [11.81]) are taken into consideration. As far as motion of solar particles in the interplanetary field is concerned, this problem was considered in detail in Section 7.

If follows from the above-mentioned facts that explanation to the motion of cosmic rays (accuracy of diffusion approximation, role and mechanism of disturbances in adiabatic invariant, mechanism of isotropization of cosmic rays) still remains an urgent theoretical problem.

Diffusion equation. Formally, it is necessary to satisfy two conditions in order to apply the diffusion equation. Firstly, concentrations of particles must satisfy the equation of continuity.

$$\frac{\partial n}{\partial t} = -\operatorname{div} F. \tag{14.1}$$

Secondly, flux F must be proportional to gradient n taken with the opposite sign:

$$F = -\varkappa \operatorname{grad} n. \tag{14.2}$$

Combining (14.1) and (14.2), we get diffusion equation

$$\frac{\partial n}{\partial t} = \operatorname{div}[\varkappa \operatorname{grad} n], \tag{14.3}$$

where diffusion coefficient $\varkappa$ can in general depend on the coordinates of the point of observation. If $\varkappa$ = const, equation (14.3) takes a very simple form:

$$\frac{\partial n}{\partial t} = \varkappa \Delta n. \tag{14.4}$$

While studying propagation of solar particles in the interplanetary space, use is often made of the solution of asymmetrical parabolic equation of the type

$$\frac{\partial n}{\partial t}=\varkappa\Delta n+\tilde{F}(r,t),\quad 0<r<\infty,\quad t>0, \tag{14.5}$$

at zero initial conditions $n(r,0) = 0$ where n is the concentration of particles; $\varkappa = \Lambda v/3$ is the diffusion coefficient of particles of velocity v and transport range Λ and $\tilde{F}(r, t)$ is the power of the source (injection function). Solution of equation (14.5) at zero initial condition in the case of a point source $\tilde{F}=\tilde{F}(t)\,\delta(r)$ has the form

$$n(r,t)=\frac{1}{(2\sqrt{\pi\varkappa})^3}\int_0^t\frac{\tilde{F}(\tau)}{(t-\tau)^{3/2}}e^{-\frac{r^2}{4\varkappa(t-\tau)}}d\tau. \tag{14.6}$$

Diffusion equation is a simple consequence of the general problem of arbitrary straying of a large number of particles without any mutual effect (see Chandrasekar [41]). In order to describe motion of particles in the interplanetary space correctly, it is necessary to use the integral (kinetic) equation (see Section 16). However, the differential equation which gives an approximate description of the process of propagation, is solved so simply that it is appropriate to use its solutions if only they are suitable.

In diffusion equation, there is first derivative of t while in the wave equation there is second derivative. This difference leads to the fact that solutions of diffusion equation are stable and singular only at $t > 0$. As is known, dependence on time for wave equation has the sinusoidal form $\exp(-i\omega t)$. However, as will be shown below, the term for diffusion equation giving dependence on time has the form $\exp(-r^2/4\varkappa t)$, i.e., it is asymmetrical with respect to t. At $t > 0$, this term decreases exponentially while at $t < 0$, amplitude of the wave infinitely increases with an increase in $|t|$.

Directional effect, with time, of the solution of diffusion equation is the result of the fact that this process reflects the behavior of some mean distribution of many particles. As it follows from the theorems in thermodynamics, nonuniformities in these mean distributions, which could exist in the beginning, get smoothened with the passage of time and it leads to an increase in entropy. It is equivalent to the confirmation that the phenomena described by diffusion equation have statistical nature (see Mors and Feshbakh [42]).

Let us mention one more important aspect. If we consider diffusion of particles from a point source in an infinite uniform medium, in the stable regime (uniform emission of particles in all directions), we get that concentration of particles decreases with distance as $\sim 1/r$ in place of the law $\sim 1/r^2$ for vacuum when the particles move from the source in straight lines (see [43]). Obviously, particles just near the source undergo first collisions at a distance equal to the mean free path. If the source is enclosed by a concentric sphere whose radius is small as compared to the mean free path, there will be a very small number of collisions in the sphere. Consequently, expression for n near the source will have the term $\sim 1/r^2$ while from the theory of diffusion, we get the law of change of concentration $n \sim 1/r$ at every value of r in the stable region.

Explanation of this paradox lies in the fact that the diffusion theory is not applicable to small distances from the source. While deriving the basic postulates of diffusion theory, it is implicitly assumed that this theory is valid at $r \gtrsim \Lambda$. Therefore, conclusions of diffusion theory are not reliable at $r \lesssim \Lambda$. In other words, solution of diffusion equation is not applicable till a time $t > \Lambda/v$ has passed after the exit of particle from the source. The diffusion theory is also not applicable at distances $r \lesssim \Lambda$ from the boundary where properties of the medium change significantly or in the system whose dimensions are comparable to Λ.

Elementary diffusion model. As is abvious from (14.6), solution of equation (14.5) at zero initial condition is defined by the form of function $\tilde{F}$. If we take $\tilde{F}(r,t) = N\,\delta(r)\,\delta(t)$ where N is the total number of particles emitted and δ is the delta function (i.e., if we consider a point and instananeous source), from (14.6) we get

$$n(r,\,t) = \frac{N}{(2\sqrt{\pi\varkappa t})^3}\, e^{-\frac{r^2}{4\varkappa t}}. \qquad (14.7)$$

At $\varkappa$ = const (diffusion in isotropic infinite medium), this solution corresponds to diffusion model which in future will be called as elementary model.

It is easy to notice that the curve (14.7) describing diffusion "wave" is asymmetrical with respect to t and has maximum at

$$t_{\max} = \frac{r^2}{6\varkappa}, \tag{14.8}$$

and the concentration at this point is equal to

$$n_m(r, t_{\max}) = \frac{N}{r^3}\left(\frac{1}{2}\sqrt{\frac{6}{\pi}}\right)^3 e^{-3/2}. \tag{14.9}$$

From the expressions (14.7) and (14.8), we directly get a number of important conclusions.

1) At $t > r^2/4\varkappa$, the exponential factor in (14.7) does not play a significant role and the concentration starts decreasing according to the law $n \sim t^{-3/2}$. This time variation of concentration is the most significant symptom of the relization of three-dimensional diffusion in the isotropic infinite medium.

2) Since intensity I is proportional to concentration of particles, the graph $\ln(It^{3/2})$ as a function of t^{-1} will be a straight line, the angle of inclination of which is determined by the parameter $-r^2/4\varkappa$ from where value of $\varkappa$ can be found out.

3) If $\varkappa = \Lambda v/3$ and Λ does not depend on the energy of particles, then $t_{\max} = r^2/2v\Lambda \sim v^{-1}$.

4) If N = N(R) is the rigidity spectrum of particles at the time of emission from the accelerating region (i.e., if it is assumed that the beam of solar particles is not monochromatic as is observed in practice) and if $\Lambda(R) \sim R^{\alpha}$, the observed spectrum after some time will have the form $n(R) \sim N(R) R^{-3\alpha/2}$ i.e., the spectrum at $\alpha > 0$ must soften with time.

Dimensions of the region being studied from the data on solar cosmic rays. As is seen from (14.9), concentration of particles, at maximum, decreases on increasing the distance from the source according to the law $\sim r^{-3}$. The distance at which the concentration of solar cosmic rays becomes comparable with the concentration of galactic cosmic particles on the Earth's orbit has been estimated in the work of L. I. Miroshnichenko [44] on the basis of (14.9).

If the spectra of protons and α-particles, obtained by McDonald and Webber [45], are used and if the ratio of intensities of α-particles and heavier nuclei is considered to be 9:1, it is possible to calculate the concentration of the total beam of galactic cosmic rays on the Earth's orbit. This value was found to be equal to 1.2×10^{10} cm^{-3} [I.21] for the minimum solar activity on the assumption that cut-off of primary spectrum in the solar system was completely absent during measurements [45] (1955-56), i.e., undistorted spectrum of galactic cosmic rays was observed. In the opposite case, the obtained value gives the lower limit of concentration. Thus, we will consider that this value corresponds to concentration of cosmic rays in the interstellar space and that at maximum solar activity, it decreases at the Earth's orbit by not more than two times ([1.2], Section 3).

Let us now use data on the maximum amplitude of the outburst for February 23, 1956 flare. According to [1.2], neutron monitors on the Earth's surface recorded an increase in intensity by $\lesssim 50$ times which corresponds to the increase in the interplanetary space by $\lesssim 10^3$ times. Thus, we get $n_{max}(r_{\oplus}) = 1.2 \times 10-7$ cm^{-3} at the Earth's orbit ($r = r_{\oplus}$). On the basis of (14.9), following relation can be written:

$$\frac{n_{max}(r_{\oplus})}{n_{max}(r_x)} = \left(\frac{r_x}{r_{\oplus}}\right)^3. \tag{14.10}$$

Putting $n_{max}(r_x) = 1.2 \times 10^{-10}$ cm^{-3}, from (14.10) we get $r_x = 10$ a.u. [44]. If the value of the diffusion coefficient $\varkappa = 2 \times 10^{22}$ cm^2 sec^{-1} is taken for relativistic particles, maximum concentration at a distance of r_x from the Sun will be observed at $t_{max}(r_x) = 2 \times 10^5$ sec. Concentration of particles at the Earth's orbit at this time can be determined from (14.7) by putting $N = 10^{32}$ particles [I, I]. From the order of parameter, $n(r_{♁})$ is found to be approximately equal to 10^{-12} cm^{-3} which constitutes ~ 1% of the concentration of galactic cosmic rays near the Earth's orbit.

According to Kane [46], neutron monitors at the Earth's surface can record fluctuations of intensity with an error of about ± 1% during the two hours of recording. Thus, at that time when concentration of solar particles becomes comparable to the concentration of galactic cosmic rays at a distance of r_x= 10 a.u. from the Sun, concentration of solar cosmic rays on the Earth's orbit will practically be beyond the limits of sensitivity of the main recording instrument, i.e., neutron monitor. It should be mentioned that the error of ± 1% refers to the values of intensity during 2 hours and therefore, application of data for lesser period of time will only reduce the recording accuracy.

It can be concluded from the above-mentioned facts that solar cosmic rays, recorded on the Earth, give information about a space of radius $\angle$ 10 a.u. This estimate should also be considered as the upper limit since the data on February 23, 1956 flare - the most powerful of all the flares observed up to this time - were used in calculations. As a matter of fact, the maximum amplitude of increase for the remaining flares was by 1-2 orders less than for February 23, 1956 flare [1.2] which decreases r_x by 2 -5 times. Consideration of the decrease in the intensity of galactic cosmic rays by 2 times at the maximum solar activity insignificantly changes the parameter r_x = 12.6 a.u

If we base upon the data of February 23, 1956 flare, an increase in the accuracy of recording to ± 0.1% during 2 hours of the operation of instruments, achieved for neutron super-monitors (see the work of Carmichael [1. 8]), can increase r_x up to 21.5 a.u. However, increase in the flux of solar particles over the background by ~ 0.1% is comparable to the amplitude of other types of variations of cosmic rays([1.2], Section 3). Thus, it can be assumed within the framework of the diffusion model under consideration that the dimensions of the region which can be studied from the measurements on solar cosmic rays are not more than 10 a.u.

Rate of diffusion. Obviously, rate of diffusion should be considered as the rate of displacement of the crest of diffusion "wave", i.e., the rate of displacement in space of the maximum intensity determined from the relation (14.8). If, as usual, we take $v_d = dr/dt$, from (14.8), we get

$$v_d = \frac{3\varkappa}{r}. \tag{14.11}$$

If the medium is infinite and uniform, the characteristic volume occupied by particles during their propagation from the point of emission increases and the concentration decreases. The value of v_d can naturally be considered equal to the rate of increase of this volume. Therefore, on the basis of (14.11), it can be written that $r = \sqrt{6\varkappa t}$. If the volume increases in k measurements, the law of conservation of number of particles, follows the requirement $nr^k \approx$ const from where we get the power law $n \sim t^{-k/2}$ for the decrease of concentration. If $k = 3$ (three-dimensional diffusion in an uniform infinite space), in accordance with (14.7), $n \sim t^{-3/2}$.

Let us compare this case of diffusion from a point source in an infinite medium with the diffusion from a source situated at some finite distance r_0 from the open boundary where n tends to zero due to free flow of particles into infinity. In the initial period (at $r \ll r_0$), solution (14.7) of the diffusion equation is valid for infinite medium; i.e., decrease of concentration follows the law $\sim t^{-3/2}$. However, in the case when a sufficiently large number of particles start reaching the boundaries and coming out of the region of diffusion, the characteristic dimension of the space occupied by particles obviously stops increasing (at least in the direction of the open boundary) and remains confined to a value of the order of r_0. According to (14.11), the average rate of diffusion in this case remains constant. Flux of particles is equal to $nv_d = n3\ \ /r_0$ and dn/dt is proportional only to n. The parameter $T_0 \sim r_0^2/\varkappa$ will obviously be the characteristic time constant. As a result, we get the exponential law of decrease of concentration: $n \sim \exp(-t/T_0)$. As mentioned by Simpson [47], constancy of the form of spectrum with time should be one of its important consequences.

14.2 Diffusion equation and nature of diffusion medium. The elementary diffusion model comes across certain difficulties. It, for example, cannot explain the anisotropy of solar particles which is observed on the Earth's surface as well as in the interplanetary space (see Sections 10 and 11). Moreover, the observed intensity of solar protons in the beginning of the outburst in some cases is less than that expected on the basis of the elementary model, i.e., graph of the dependence for some interval of time which, for example, for September 28, 1961 flare coincides with the duration of anisotropy (about 1.5 hrs.). Explanation of this effect can obviously be found by modifying the elementary model by considering the nature of the diffusion medium.

Nature of the medium is accounted for in the equation (14.5) by the diffusion coefficient. In an isotropic medium, diffusion coefficient is a scaler $\varkappa_0$ which in the kinetic theory is expressed by $\Lambda v/3$. As shown by Allis [48], diffusion coefficient in the presence of a regular magnetic field is a tensor defined by the relation

$$F_i = -\mathrm{grad}_i(\varkappa_{ij}n), \tag{14.12}$$

where F_i the i-th component of the flux of particles and n is the concentration (i = 1,2,3). Tensor $\varkappa$ described through matrix has the form

$$\varkappa_{ij} = \varkappa_0 \begin{vmatrix} 1 & 0 & 0 \\ 0 & \frac{\nu^2}{\nu^2+\omega^2} & \frac{-\omega\nu}{\nu^2+\omega^2} \\ 0 & \frac{\nu\omega}{\nu^2+\omega^2} & \frac{\nu^2}{\nu^2+\omega^2} \end{vmatrix}, \tag{14.13}$$

where $\nu = v/\Lambda$ is the frequency of collisions of particles with irregularities of the magnetic field and $\omega = eH/mc$ is the Larmorov frequency in the regular field H.

Equations (14.12), (14.13) along with the continuity equation (14.1) give

$$\frac{\partial n}{\partial t} = \frac{\varkappa_0}{r^2}\left\{\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \bar{\gamma}L(\theta, \varphi)\right\}n, \tag{14.14)}$$

where

$$L(\theta, \varphi) = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\varphi^2}, \qquad (14.15)$$

$$\bar{\gamma} = v^2/(v^2 + \omega^2). \qquad (14.16)$$

The equation (14. 14) must be supplemented by the initial conditions.

$$n(\mathbf{r}, 0) = \frac{N}{r_\odot^2}\delta(\mathbf{r} - \mathbf{r}_\odot) = \frac{N}{r_\odot^2}\delta(r - r_\odot)\delta(\mu - \mu_0)\delta(\varphi - \varphi_0), \quad (14.17)$$

where N is the total number of particles of velocity v emitted at $t = 0$ at the point $r = r_\odot$, $\mu = \mathrm{Cos}\,\theta_0$, $\mu_0 = \mathrm{Cos}\,\theta_0$. Thus, equations (14. 14)-(14. 17) completely define space-time distribution of solar particles in the interplanetary space with the consideration of the position of chromosopheric flare on the Sun's disk (Fig. 14. 1)

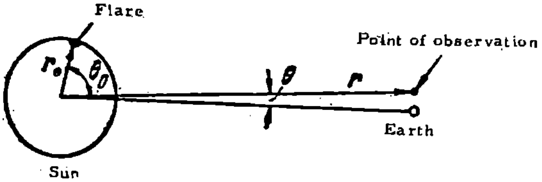

Fig. 14. 1. Consideration of the position of chromospheric flare on the Sun while solving diffusion equation for solar parricles.

In the limiting case of very strong magnetic field ($\omega \to \infty$, $\nu \to 0$), solution of equation (14. 14) at initial conditions (14. 17) has the form (see Fibich and Abraham [49])

$$n(r, t) = \\ = \frac{N}{(4\pi\varkappa_0 t)^{1/2}}\frac{1}{r r_\odot}\left\{\exp\left(-\frac{(r - r_\odot)^2}{4\varkappa_0 t}\right) - \exp\left(-\frac{(r + r_\odot)^2}{4\varkappa_0 t}\right)\right\} \times \\ \times \delta(\mu - \mu_0)\delta(\varphi - \varphi_0) \qquad (14.18)$$

This expression is essentially superposition of solutions of the one-dimensional diffusion equation. It is not strange since in the case of a very strong field, particles emitted at the point $r_\odot$ have very small radius of curvature and therefore, can propagate only along the natural line of force passing through this point. If $r_\odot \to 0$, i.e. if the beginning of flare is displaced to the point of convergence of the radial lines of force, in the limiting case, we get

$$\lim n(r, t) = \frac{4\pi N}{(4\pi\varkappa_0 t)^{3/2}} \exp\left(-\frac{r^2}{4\varkappa_0 t}\right), \qquad (14.19)$$

which coincides with the solution for the case of three-dimensional diffusion.

Let us now study the case of a strong but infinite magnetic field when the condition $\tilde{\gamma} \ll 1$ is satisfied. This condition means that $\omega\tau \ll 1$ where $\tau = v^{-1}$ is the average interval between collisions. If the mean free path $\Lambda = v\,\tau$ does not depend on the velocity, this condition can be written as $\Lambda\rho \ll 1$ where ρ = cp/eH is Larmorov radius of particles. Under certain simplifying assumptions, the following expression was obtained in [49]

$$n(r, t) = \frac{1}{\tilde{\gamma}} \cdot \frac{N}{(4\pi\varkappa t)^{3/2}} \exp\left\{-\frac{(r-r_\odot)^2}{4\varkappa t} - \frac{r r_\odot \theta_0^2}{4\tilde{\gamma}\varkappa t}\right\}, \qquad (14.20)$$

where the effect of magnetic field (factor $1/\tilde{\gamma}$) and position of chromospheric flare (point with coordinates $r_\odot$, $\theta_\odot$) have been taken into account. It is seen from (14. 20) that in this case, there must be exponential anisotropy at the observation point. Expression (14.20) is similar to the result obtained earlier by V.I. Shishov [50] where the differential approach was used for solving the problem. Simultaneous measurements during one flare with the help of many space rockets are apparently necessary for confirming the angular dependence of concentration of particles in the interplanetary space.

Comparison of the results (14. 18) and (14.20) facilitates the assumption about the possibility of transition (during initial stage of the event) from one-dimensional to three-dimensional diffusion. The transition time should probably depend on the intensity of magnetic field. Study of this problem on the basis of Boltzman's equation (see Section 16.5) helped to get the simple relation $t_t = \sqrt{3\xi/\rho\nu} \sim \xi H_0/\nu p$ for transition time where ξ is the distance of observation point from the axis of the regular magnetic field. Thus, higher the intensity of the regular component of the interplanetary field,. more will be t_t and more effective the mechanism of scattering of particles (factor ν^{-1}), the lesser will be t_t. Moreover, it can be seen from the expression for t_t that the transition time is inversely proportional to the momentum of particles.

Scattering of particles at the irregularities of the field in the presence of a weak but extending regular magnetic field was also studied by L.I. Dorman [51]. It was shown that for particles of sufficiently high energy ($cp \gtrsim ZeH_0\Lambda$), the diffusion will be isotropic. The significant dependence of the outburst amplitude on the position of chromospheric flare on the Sun should not be observed for such particles. On the other hand, diffusion of low-energy particles ($cp \ll ZeH_0\Lambda$) will only be along the field and the diffusion transverse to the field will practically be absent, i.e., this problem to a first approximation can be considered as a one-dimensional problem.

If $cp \sim ZeH_0\Lambda$, the diffusion will mainly be along the field but diffusion transverse to the field should also taken into consideration. The critical case $cp_{cr} = ZeH_0\Lambda$ is of great interest. A study of large and small flares of cosmic rays shows that cp_{cr} changes from event to event in extremely wide limits depending on the state of the interplanetary medium but the most probable value is apparently of the order of a few Gev. To be certain, if we assume $cp_{cr} \sim 3$ Gev for protons and considering that for such energies $\Lambda \sim 10^{12}$ cm, it is possible to estimate the intensity of the regular component of the interplanetary magnetic field $H_0 \gtrsim 10^{-5}$ gauss which is in agreement with the results of direct measurements by space rockets (see, for example, the work of Coleman [20]).

14.3 Possibility of the existence of magnetic boundary of the diffusion region. As shown in Section 10, intensity of solar cosmic rays in some cases decreases according to an exponential law. This fact can be related to the presence of a boundary of diffusion region at a distance r_0 from the Sun. In this case, the problem of propagation of solar particles in a limited spherically symmetrical medium $0 \leqslant r \leqslant r_0$ is solved at the following initial and boundary conditions: $n(r, 0) = n_0$ and $n(r_0, t) = 0$. Solution of such a problem has the form

$$n(r,\ t)=\frac{2n_0r_0}{\pi r}\sum_{j=1}^{\infty}\frac{(-1)^{j+1}}{j}\sin\frac{\pi rj}{r_0}\exp\left[-\frac{\pi^2j^2\varkappa t}{r_0^2}\right], \qquad (14.21)$$

where $\varkappa$ is the value of diffusion coefficient averaged along whole of the diffusion volume and $\varkappa$ = const at $r \lesssim r_0$ and $\varkappa \to \infty$ at $r \geqslant r_0$. It can be shown that at $t \gtrsim r_0^2/\pi^2\varkappa$, contribution of the terms with $j > 1$ to the sum of series (14.21) is $\lesssim 1\%$. Therefore, they can be neglected:

$$n(r,\ t)=\frac{2n_0r_0}{\pi r}\sin\frac{\pi r}{r_0}\exp\left[-\frac{\pi^2\varkappa t}{r_0^2}\right]. \qquad (14.22)$$

It is not difficult to show that the solutions (14.7) and (14.22) coincide with an accuracy up to the constant factor right up to the time determined by the relation $t \approx r_0^2/10\varkappa$. Starting from this time the concentration must decrease according to the exponential law $n \sim \exp(-t/T_0)$ where the time constant of attenuation

$$T_0=\frac{r_0^2}{\pi^2\varkappa}\approx\frac{r_0^2}{10\varkappa}. \qquad (14.23)$$

If (14.22) is represented in the form of dependence of ln n on t, angle of inclination of the obtained straight line will be defined by the parameter T_0 simultaneously related to two unknown parameters $\varkappa$ and r_0. It should be mentioned that if $r_0 > r_♁$, during observations on the Earth's orbit, it is possible to use the solution (14.7) up to the time till the crest of diffusion "wave" attains a distance of r_0. Thus, by fixing the maximum outburst near the Earth and by determining the value of $\varkappa$ from (14.8), it is possible to get the value of T_0 from (14.23) by putting $\varkappa$ = const right up to $r \simeq r_0$. As will be shown in Section 14.4, diffusion coefficient depends on the rigidity of particles. Therefore, if $\varkappa$ is obtained by averaging along a wide interval of energies, the value of r_0 in the case of exponential decrease will correspond to some effective boundary. It follows from this that $T_0 = T_0(R)$ and the a values of T_0 and r_0 must decrease with an increase in rigidity.

The exponential decrease was for the first time observed in the measurements of Anderson et al. [III. 90] for May 4, 1960 flare. Afterwards, a similar effect was observed in a number of other cases. Most of the experimental data on this problem are summed up in Table 14.1. Obviously, the data of this Table should be analyzed by considering the conditions under which one or the other outburst was observed. For example, from the data on 1st outburst on November 12, 1960, the unambiguous conclusion should not be drawn that T_0 increases with an increase in R since the electromagnetic situation in the interplanetary space during this period was extremely complicated.

The dependence T_0 (R) can be studied only for a specific flare with the help of data on particles of different energies. It is obvious from Table 14.1 that September 28, 1961 [1.23] and February 5, 1965 [III.102] flares are most suitable for this purpose. Dependence T_0(R) for these flares is shown in logarithmic scale in Fig. 14.2. It is seen that $T_0 \sim R^{2.5 \pm 0.5}$ in the rigidity range of 0.6 - 1.2 Gv. The value $T_0 = 6.5 \pm 0.5$ hrs, calculated by us for January 28, 1967 flare lies well on the obtained straight line. From the measurement data of Heristchi et al. [III.107] for the July 7, 1966 flare, it is possible to get the value $T_0 =$ 4-5 hrs which is close to the value of T_0 for September 28, 1961 flare at R > 1.2 Gv.

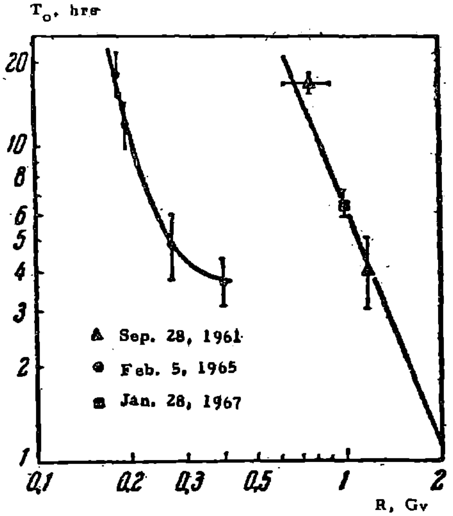

Fig. 14.2. Attenuation time constant as a function of rigidity of particles for the flares of September 28, 1961, February 5, 1965 and January 28, 1967.

The situation gets complicated at very low rigidities. As is obvious from Table 14.1 and Fig. 14.2, time variation of

TABLE 14.1

Data on magnetic boundary of the diffusion region

Date of flare	Measurement method	R, Gv	T_Ω, hrs.	Λ, cm	υ, a. u.	References	Remarks
Feb. 23, 1956	Ground network	> 1	—	$> 10^{12}$	$\geqslant 5$	[I.2]	
May 4, 1960	» »	> 1	0,284	—	—	[III.90]	Beginning of the decrease
	» »	> 1	1,3	—	2,16*	[III.90]	End of the decrease
Sept. 3, 1960	Balloons	$> 1,34$	23	$> 3 \cdot 10^{11}$	2,2	[III.78]	
Nov. 12, 1960	Ground network	< 4	$1 \div 3,5$	—	—	[III.81]	II outburst μe
		$< 1,3$	6,6	—	—	[III.82]	I outburst не
	» »	$> 0,0018$	2	—	—	[III.82]	» »
	» »	> 1.10	5	—	—	[III.82]	» »
	» »	$> 1,05$	6	—	—	[III.82]	» »
	» »	$> 0,98$	6	—	—	[III.82]	» »
	» »	$> 1,38$	11	—	—	[III.82]	» »
	» »	$> 0,0018$	$3,5 \div 4$	—	—	[III.82]	II outburst не
Nov. 15, 1960	» »	< 4	4,5	—	—	[III.81]	
	» »	$> 0,0018$	5	—	—	[III.72]	
	» »	> 1	—	—	2,5	[4]	Reflecting boundary
June 18, 1961	Balloons	$> 1,34$	8,9	$2,25 \cdot 10^{11}$	1,8	[III.88]	
July 20, 1961	»	$0,136 \div 1,34$	5,3	$3,45 \cdot 10^{11}$	1,7	[III.88]	
Sept. 28, 1961	"Explorer-12"	$0,64 \div 0,95$	16 ± 2	$(6 \div 7) \cdot 10^{11}$	$3,1 \pm 0,3$	[1.55]	
	» »	$> 1,21$	4 ± 1	$(6 \div 7) \cdot 10^{11}$	$1,8 \pm 0,2$	[1.55]	
Feb. 5, 1965	Polar satellite *	$> 0,136$	$16,8 {+2,7 \atop -2,2}$	—	—	[III.102]	
	» »	$> 0,194$	$11,6 {+2,1 \atop -1,6}$	—	—	[III.102]	
	» »	$> 0,276$	$4,7 {+1,3 \atop -1,0}$	—	—	[III.102]	
	» »	$> 0,395$	$4,0 {+0,3 \atop -0,9}$	—	—	[III.102]	
	"Mariner-4" 1.14 a.u	$> 0,136$	18,33	—	—	[III.127]	
	"IMP-2" (1 a.u.)	$> 0,05$	13,2	—	—	[III.127]	
July 7, 1966	Balloons	$\geqslant 1,0$	$4 \div 5$	$(6 \div 9) \cdot 10^{11}$	$1,7 \pm 0,1$*)	[III.107]	
Jan. 28, 1967	Ground network	$> 0,98$	$6,5 \pm 0,5$	$\gtrsim 3 \cdot 10^{11}$	$2,5 \pm 0,1$	[52]	

* Estimate in this work.

protons with $R = 0.18\text{-}0.20$ Gv significantly differs from that of protons having $R > 0.25$ Gv. It can be explained by assuming that the source has a spectrum with variable γ or that the propagation of particles differs from simple diffusion (for example, Λ depends on R).

Had the radius of diffusion region been independent of the rigidity of particles (had r_0 been the boundary fixed in space), the characteristic attenuation constant T_0, according to (14.23), would have been defined only by the diffusion coefficient. The relation $T_0 \sim v \sim R^{-1}$ would have been fulfilled in the non-relativistic region at Λ = const. At relativistic energies, the relation should be $T_0 \sim \Lambda^{-1}$ from where, taking into account the results of Section 14.4, we again get $T_0 \sim R^{-1}$. The fact, that this relation does not conform to experimental data given in Fig. 14.2, can testify to the presence of the dependence $r_0(R)$ which is defined by the structure of interplanetary magnetic field at large distances from the Sun. If the relation $T_0 \sim R^{2.5+0.5}$ is valid in a wide range of rigidities, on the basis of the above-mentioned facts we get $r_0 \sim R^{(-0.5-1)}$. Thus, it follows from these rough estimates that the radius of diffusion region at medium and high rigidities will hardly depend on the rigidity of particles. If it is assumed that $r_0 \sim \exp(-R/R_0)$, we get $R \sim 1$ Gv from the data on September 28, 1961 flare.

Some examples of diffusion in a finite uniform medium have been studied in [1.61]. Diffusion through a thick spherical shell at large values of t essentially leads to the same result as in the case of a limited sphere r_0. The tendency to an exponential decrease of intensity which was observed at the final stage of the February 28, 1956 flare [1.4] can serve as an argument in the favor of such a model. The problem of diffusion from a finite volume in the thick spherical shell, in the beginning filled with solar particles, should be considered in the presence of magnetic field mainly having radial direction inside the Earth's orbit. If the Earth is included in the injection cone, the transition from power decrease to exponential decrease will be defined by the relative dimensions of the cone and of the diffusion region. The case, when the Earth is situated in the shell at a distance from the base of the injection cone and especially, when the particles are emitted from a flare on the back side of the Sun, is of great interest. In this case, the power decrease according to the law $\sim t^{-3/2}$ can be observed for a long interval of time only near the emission point (near the base of the injection cone). The intensity at the Earth, almost immediately after attaining the maximum value, should decrease according to the exponential law while the maximum intensity, owing to prolonged diffusion of particles around the Sun and exit from the shell, will not be more than 1% of the maximum intensity of particles generated on the visible side of the Sun.

Equation of one-dimensional diffusion in a limited layer of thickness x_0 and having an absorbing boundary is studied in the work of G. F. Krymskii [53]. The comparison of the obtained solution with the experimental data on February 23, 1956 and May 4, 1960 flares favors the assumption that the region of diffusion of solar cosmic rays was limited during these flares. According to the estimates [53], dimensions of diffusion region are $x_0 \lesssim 0.7$ a.u. and $x_0 \lesssim 3.0$ a.u. respectively for the flares of May 4, 1960 and February 23, 1965. According to L. I. Dorman and G. I. Freidman [54], analysis of spreading of the effect of February 23, 1965 flare on the Earth shows that the intensity of solar cosmic rays is almost isotropic during the attenuation period. Therefore, it can be considered that the diffusion region during this period actually extended beyond the Earth's orbit. According to the data of McCracken [4], the observed anisotropy of the beam of solar cosmic rays on May 4, 1960 proves the fact that the diffusion region was mainly situated in the Earth's orbit. The results obtained in [53] agree with the views about the radial nature of the interplanetary magnetic field twisted by the rotation of the Sun.

Constancy in the form of spectrum of solar particles from February 23, 1956 flare (see Section 2) with the passage of time (within the limits of experimental errors) can serve as an additional argument in favor of the assumption that the diffusion region is limited. It should be mentioned that such an effect can be observed only when $\varkappa$ is independent of rigidity or under the condition that r_0 = const.

The problem of the existence of a magnetic limit of diffusion region also attracts the attention of research workers owing to the difficulties of the general theory of modulation of cosmic rays in the solar system (for example, see the works of Sekido and Murakami [55] and of Davis [56]).

The problem regarding the limit of diffusion region is considered in a slightly different aspect by McCracken [4] who puts forward the assumption about the existence, in the interplanetary field, of a clearly-defined magnetic barrier at $r_0 = 2.5$ a.u. which reflects the solar particles. This assumption was necessary for explaining the 30-minute delay in the beginning of the effect from November 15, 1960 flare for stations situated on the nocturnal side of the Earth during this period as compared to the stations situated on the diurnal side. Moreover, in this way, it was possible to explain the rate of subsequent outburst at stations on the nocturnal side of the Earth. McCracken's assumption [4] essentially eliminates Simpson's model [47] since the mechanisms of magnetic reflection in these models extend to large volumes in space ($r_0 \sim 5$ a.u. [47]) and it will make the appearance of a sharply defined impulse of the outburst of intensity of solar particles on the nocturnal side of the Earth impossible.

The existence of magnetic boundary is doubted in the work of Warwick [57] because of the fact that solar cosmic rays from chromospheric flares on the invisible side of the Sun are not observed if the November 20, 1960 event is not taken into account. According to Carmichael and Steljes [58], a small ($\lesssim 10\%$) increase in the intensity of cosmic rays was recorded by different ground stations on this day in the absence of flares of class > 1 on the visible side of the solar disk. According to observations of Hansen [111.85] on large eruptive protuberances, the only convincing cause of the observed increase can be the flare in the active region with the longitude 12° to the west of the central meridian, i.e., 30° from the edge of the disk.

Thus, the problem of magnetic boundary of diffusion region remains far from being clear. The fact that r_0 depends on the rigidity of particles, apparently points out the change in the scattering properties of the interplanetary magnetic fields on increasing the distance from the Sun. Therefore, it is very important to study the dependence $T_d(R)$ in different rigidity ranges (from the data on ground, stratospheric and satellite measurements).

Regular observations on comets (see the review of S.K. Vsekhvyatskii [59]) can apparently give valuable information on the structure of field at distances $\lesssim 10$ a.u. from the Sun.

14.4 Dependence of diffusion coefficient on the energy of particles and the irregularity spectrum of the interplanetary magnetic field. Numerous experimental data and theoretical calculations show that the diffusion coefficient increases on increasing the energy of particles. Therefore, the times of maximum intensities for particles of different energies will be different, shifting towards smaller values of t on increasing the energy and in accordance with (14.8), satisfying the condition $t_{max} \sim \varkappa^{-1}$. From this, we get a simple practical method of calculating the dependence $\varkappa(\mathcal{E}_k)$. As a matter of fact, taking $\varkappa$ in the form $\varkappa \sim \mathcal{E}_k^{a_1}$, we get the relation $t_{max} \sim \mathcal{E}_k^{-a_1}$ Calculating values of t_{max} from this formula for different values of a_1 along whole of the energy spectrum of solar cosmic rays and comparing the results with the experimental values of $\varkappa$ near the Earth's orbit, it is possible to draw specific conclusions about the value of a_1. Such calculations were done by L. I. Dorman and L. I. Miroshnichenko [60] (also see V. K. Budilov et al. [61]) for values of a_1 from 0.1 to 1.0 and values of $\mathcal{E}_k$ from 1 Mev to 20 Gev. From (14.8) and from the above-mentioned facts follows the obvious relation

$$\frac{t_1}{t_2} = \frac{\varkappa_2}{\varkappa_1} = \left(\frac{\varepsilon_{\kappa_2}}{\varepsilon_{\kappa_1}}\right)^{a_1} \tag{14.24}$$

Taking $\varkappa_1 = 5.5 \times 10^{21}$ cm^2 sec^{-1}, obtained by A. N. Charakhch'yan and T. N. Charakhch'yan [62] from stratospheric data on protons with $\mathcal{E}_k \approx 0.5$ Gev, and $\varkappa_2 \approx 2.75 \times 10^{22}$ cm^2 sec^{-1}, obtained by A. N. Charakhch'yan et al. [63] from the data of ground measurements during large flares (for example, on February 23, 1956 and May 4, 1960) for protons with $\mathcal{E}_k \approx$ 5.0 Gev, it is possible to notice that the value $a_1 \approx 0.7$ corresponds to such a ratio of $\varkappa_1 / \varkappa_2$. If $\varkappa(\mathcal{E}_k) = v(\mathcal{E}_k)\Lambda(\mathcal{E}_k)/3$ and if the relativistic expression (7.7) is used for the velocity of particle, we get

$$\Lambda(\varepsilon_\kappa) = \text{const} \cdot \varepsilon_\kappa^{a_1}\left[1 - \left(1 + \varepsilon_\kappa/\varepsilon_0\right)^{-2}\right]^{-1/2}. \tag{14.25}$$

According to (7.7), velocity of particles $v \sim \mathcal{E}_k^{0.5}$ at $\mathcal{E}_k \ll \mathcal{E}_0$ and $v \approx c = \text{const}$ at $\mathcal{E}_k \gg \mathcal{E}_0$ which leads to different nature of the dependence of transport range on kinetic energy : $\Lambda(\mathcal{E}_k) \sim \mathcal{E}_k^{a_1 - 0.5}$ at $\mathcal{E}_k \ll \mathcal{E}_0$ and $\Lambda(\mathcal{E}_k) \sim \mathcal{E}_k^{a}$ at $\mathcal{E}_k \gg \mathcal{E}_0$. This difference is obvious from Fig. 14.3 where the results of calculation of Λ from (14.25) are given in the logarithmic scale;

moreover, the energy scale has been replaced by scale of rigidities R and the conversion factor Λ (1Gv) $\doteq$ 1 has been used Studying the expression (14.25) for extreme points, it can be ascertained that the curve $\Lambda(\mathcal{E}_k)$ has minimum at $\mathcal{E}_k = \mathcal{E}_0 \left[-1.5 \pm \sqrt{a^{-1}_1 + 0.25}\right]$. This fact limits the range of possible values of a_1 from below since existence of minimum in the curve $\Lambda(\mathcal{E}_k)$ at $a_1 \leq 0.5$ contradicts the usually adopted dependence of Λ on $\mathcal{E}_k$ (the parameter Λ must increase or at least remain constant on increasing the kinetic energy of a particle). At the remaining values $a_1 > 0.5$, a slow growth of Λ is observed for low energies and the rate of change of $\Lambda(\mathcal{E}_k)$ increases significantly starting from the energies of the order of a few hundred Mev.

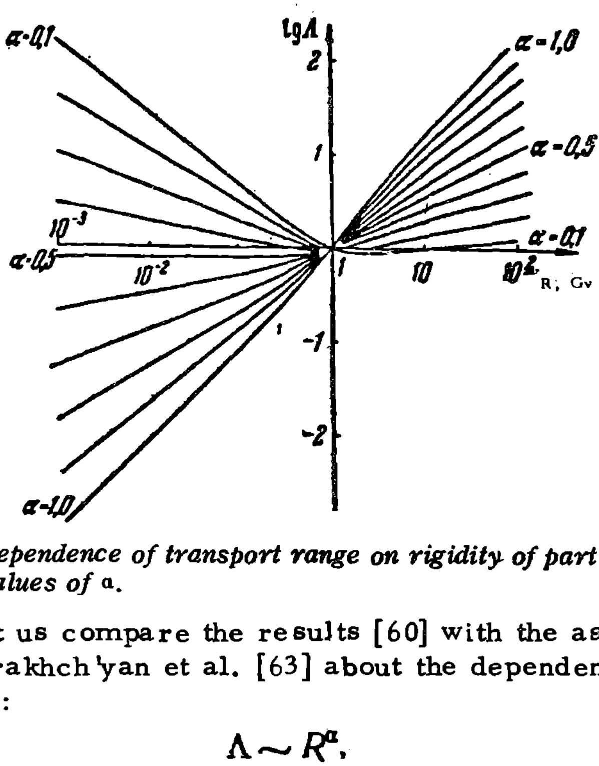

Fig. 14. 3. Dependence of transport range on rigidity of particles at different values of a.

Let us compare the results [60] with the assumption of A. N. Charakhch'yan et al. [63] about the dependence of Λ on rigidity R :

$$\Lambda \sim R^{a}, \tag{14.26}$$

where $a = 0.5$. From (14.26), we get $\Lambda \sim \mathcal{E}_k^{0.25}$ at $\mathcal{E}_k \ll \mathcal{E}_0$. This result is in accordance with the dependence $\Lambda \sim \mathcal{E}_k^{0.2}$ which follows from (14.25) at $a_1 = 0.7$. In the relativistic region, from (14.25) we get $\Lambda \sim \mathcal{E}_k^{0.7}$ while from (14.26), it follows that $\Lambda \sim \mathcal{E}_k^{0.5}$ on considering that the rigidity at $\mathcal{E}_k \gg \mathcal{E}_0$ is defined by the relation $R \sim \mathcal{E} \sim \mathcal{E}_k$ where $\mathcal{E}$ is the total energy of a particle. On transition from the dependence $\Lambda(R)$ to $\varkappa$ $(\mathcal{E}_k)$, by considering (14.26) we get $\varkappa \sim \mathcal{E}_k^{0.75}$ and $\varkappa \sim \mathcal{E}_k^{0.5}$ for non-relativistic and relativistic regions respectively. Thus, at $\mathcal{E}_k >> \mathcal{E}_o$, there is some difference between the results given in [60] and [63] which, of course is not significant due to low accuracy of determining a and a_1.

The experimental data, obtained by Bryant et al. [1.23] for the September 28, 1961 flare, made it possible to correct the values of a_1 and to detail the dependence $\varkappa(\mathcal{E}_k)$ in different energy ranges. The details were worked out by L. I. Dorman and L.I. Miroshnichenko in [64] and t_{max}, $\varkappa$ and Λ were evaluated on the basis of the data [1.23] at different energies of solar particles in the range $\mathcal{E}_k$ = 10-500 Mev. As already mentioned, data of "Explorer-12" [1.23] are of exceptional interest since the satellite at the time of flare was situated at a distance of about 80, 000 km from the center of the Earth (beyond the limits of magnetosphere) which facilitated measurement of differential spectrum of protons with $\mathcal{E}_k \gtrsim 2$ Mev for nearly 2 days after the chromospheric flare.

A flare of class 3 or 3^+, recorded, in particular, by Moreton [65], occurred on September 28, 1961 in the active region of the Sun with coordinates of 15°N and 29°E. The flare commenced at 2202 UT and attained maximum brightness in H_a-line at 2234 UT on September 28, 1961 and finished at 0130 UT on September 29, 1961. Observatories of the eastern hemisphere were situated on the noturnal side of the Earth during this period. According to the observations of Anderson and Winckler [66], the chromospheric flare was accompanied by X-ray radiation which started at 2207 UT and attained maximum at 2217 UT. At the same time, radio emission of II, III and IV types was observed by Maxwell [67] but the main radio outburst was recorded 22 minutes before the X-ray flare. Jean and Crary [68] also observed a change in the phase of low-frequency signals reflected from the ionosphere especially over Uruguay at 2217 UT i. e., at the time of maximum X-ray radiation. The magnetic field was quiet during the chromospheric flare. According to data [1. 23], a large magnetic storm commenced at 2108 UT on September 31, 1961 (with sudden commencement) which was accompanied by Forbush decrease in the intensity of cosmic rays on the Earth's surface. The Forbush effect was studied by Patel and Cahill [69] and was also observed on satellite "Explorer-12" by Bryant et al. [I. 23].

The chromospheric flare was accompanied by generation of solar cosmic rays which were recorded by Bryant at el. [I.23] on "Explorer-12" and by Van Allen and Whelpley [70] on "Injun-1".

Curves of time variation of the intensity of solar protons on the Earth's orbit, for different values of kinetic energy, are plotted in Fig. 14.4 on the basis of data [1.23] and it was assumed that the particles were emitted at the time of commencement

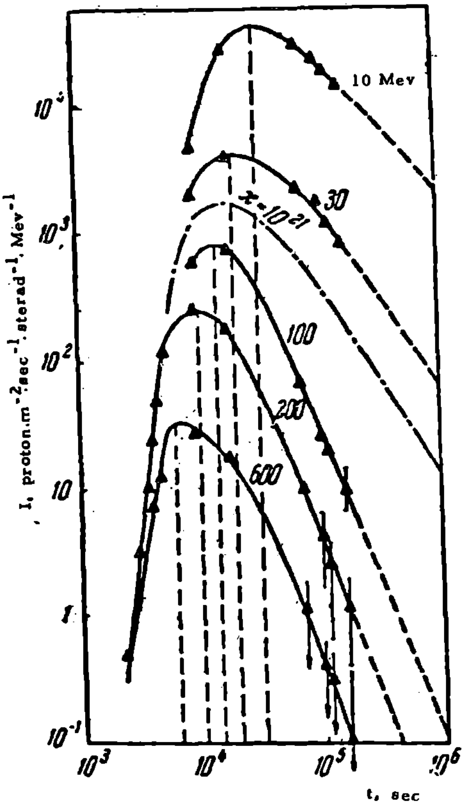

Fig. 14.4. Time variation of solar protons of different energy from September 28, 1961 flare. Calculated diffusion curve for $\varkappa = 10^{21}$ *cm*^{2}*/sec is shown by dotted lines.*

of the flare of X-rays (i.e., at 2207 UT or 5 minutes after the commencement of chromospheric flare). The calculated curve obtained from (14.7) in arbitrary units at $\varkappa = 10^{21}$ cm^2 sec^{-1} is also given for comparison. It is seen that for particles with $\mathcal{E}_k = 10$ and 30 Mev, the intensity after maximum, decreases approximately according to the law $\sim t^{-3/2}$ in accordance with (14.7) while the intensity of particles with $\mathcal{E}_k \geqslant 100$ Mev at large values of time has a tendency to decrease rapidly (approximately according to the law t^{-2} to $t^{-2.5}$). On the basis of Fig. 14.4 and formula (14.7), values of t_{max}, $\varkappa$ and Λ were determined in [64] for protons in the energy range of 10-500 Mev.

Curves of the dependence of t_{max}, $\varkappa$ and Λ on the kinetic energy of protons are shown in Fig. 14.5. For particles with $\mathcal{E}_k = 10$-500 Mev, t_{max} changes from 3.16×10^4 sec to 6.3×10^3 sec while $\varkappa$ lies within the limits $(1.2$-$6.0) \times 10^{21}$ cm^2.sec^{-1}. It is interesting to mention that the value of diffusion coefficient for particles with $\mathcal{E}_k = 500$ Mev ($\varkappa = 5.5 \times 10^{21}$ cm^2.sec^{-1}) is exactly equal to the value obtained by A.N. Charakhch'yan and T.N. Charakhch yan [62] from the staratospheric data on May 4 and September 3, 1960 flares.

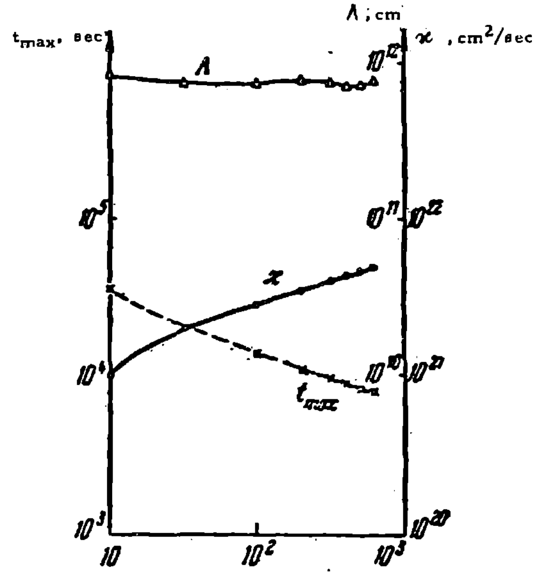

Fig. 14.5. Dependence of time of maximum, diffusion coefficient and transport range on the energy of particles for September 28, 1961 flai [64].

If the dependence of diffusion coefficient on energy is approximated by the expression $\varkappa \sim \varepsilon_k^{\alpha_1}$, from Fig. 14.5, we get $\alpha_1 \gtrsim 0.5$ in the energy range of 10-600 Mev. As shown above, parameter α_1 cannot be less than 0.5 in the framework of the elementary diffusion model. According to Fig. 14.3, the transport range at $\alpha_1 = 0.5$ should practically remain constant in the energy range under consideration. This conclusion is confirmed by the graph of $\Lambda(\varepsilon_k)$ in the upper part of Fig. 14.5 where the value of Λ changes within the limits $(6-8) \times 10^{11}$ cm. A similar result was obtained in the work of Bryant et al. [I.54] in which the distance covered by particles in the interplanetary space before attaining maximum intensity was evaluated. This distance in vt_{max}/c units was found to be practically constant in the energy range of 1.4-500 Mev from where it follows that $\Lambda =$ const while the diffusion coefficient was determined only from the velocity of particles: $\varkappa \sim v \sim R^{10}$ A similar dependence was also observed by the authors [I.54] for the flares of November 10, 1961 (in the energy ranges of 1.4-22 Mev and 55-500 Mev) and October 23, 1962 (4-330 Mev). Indications on constancy of Λ in the range ~40-50 Mev were also obtained by A.N. Charakhch'yan and T.N. Charakhch'yan [71] for the flares of September 3, 1960, November 15, 1960 and January 28, 1967 by comparing the time variation of solar protons in stratosphere over Murmansk and Churchill (neutron supermonitor). These results, summed up in Table 14.2, make

TABLE 14.2

Behavior of Λ at nonrelativistic energies

Date of flare	Energy range, Mev	$\Lambda/10^{11}$, cm	References
Sept. 3, 1960	40 - 500	4	[71]
Nov. 15, 1960	40 - 500	7.1 - 7.6	[71]
Sept. 28, 1961	1.4 - 500	6	[I.54]
Sept. 28, 1961	10 - 500	6 - 8	[64]
Nov. 10, 1961	1.4 - 22	9	[I 54]
Nov. 10, 1961	55 - 500	8.25	[I.54]
Oct. 23, 1962	4 - 330	9	[I.54]
Jan. 28, 1967	40 - 500	7.3 - 7.4	[71]

it possible to confirm that dependence $\varkappa(\mathcal{E}_k)$ in the nonrelativistic region is, in general, satisfactorily described by the power function $\varkappa \sim \mathcal{E}_k^{0.5}$, i.e., $\varkappa \sim v \sim R$ at Λ = const*.

The values of diffusion coefficient, obtained by Hofmann and Winckler [III.88] from the data of stratospheric measurements at high latitudes in July 1961 (2.2×10^{21} cm^2·sec^{-1} and 3.4×10^{21} cm^2·sec^{-1} for the flares of July 18 and 20 respectively), obviously, do not contradict the results of L.I. Dorman and L.I. Miroshnichenko [64], because the stratospheric measurements in July 1961 were taken almost in the same energy range as on "Explorer-12" and therefore, the values of $\varkappa$ should almost be the same (if the conditions in the interplanetary medium were approximately the same for these events).

It should be pointed out that the above-mentioned estimates of $\varkappa$ and Λ are applicable only to protons and to the case of uniform distribution of scattering centers in the solar system. Consideration of irregularities in the distribution of magnetic clouds and their movement in the interplanetary space leads to the dependence of $\varkappa$ and Λ on the distance from the Sun and to the dependence of the time of maximum intensity on the velocity of magnetic irregularities (see Sections 14.6 and 14.9).

The method based on the application of formula (14.24) contains the possibility, in principle, of differentiating the beams of solar protons and heavier nuclei owing to low rate of motion of nuclei with $Z > 1$ in the interplanetary magnetic field (it is about double in the nonrelativistic region) as compared to protons of same rigidity.

In connection with the question under consideration, it is necessary to mention two interesting results referring to the dependence of $\varkappa(\mathcal{E})$ in the case when diffusion takes place in the electromagnetic medium of the solar corpuscular beam. While studying the diffusion of galactic cosmic rays in the turbulent magnetizing cloud (corpuscular beam), Kitamur [72] found the dependence $\varkappa \sim \mathcal{E}^{0.2}$ for particles of velocity $v \sim c$ from

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Physical sense of Λ is not at all obvious but the condition Λ = const points out the approximate constancy of properties of the interplanetary magnetic field.

where it follows that the transport range for diffusion is $\Lambda \sim R^{0.2}$. This result is difficult to explain within the framework of the elementary diffusion model since, as it follow from (13.8), the dependence Λ (R) at $v \sim c$ should be of the form $\Lambda \sim R^2$. On the other hand, for nonrelativistic solar particles propagating in the corpuscular beams (for example, on April 1, 1960; November 15, 1960 and on July 18, 1961), A.N. Charakhch'yan and T.N. Charakhch'yan [III. 2] found that $\varkappa \sim v$ from where it follows that Λ = const. The last result does not contradict the estimates of L.I. Dorman and L.I. Miroshnichenko [64] for Λ (ε_k) from the data on September 28, 1961 flare with the only difference that the results [64] refer to steady interplanetary medium. Thus, there is no basic difference between the diffusion of nonrelativistic particles in the quiet medium and their motion in the corpuscular beam.

Important results on the dependence Λ(R) were obtained by Yu.I. Stozhkov and T.N. Charakhch'yan [73] from the results of the study of the spectrum of 11-year variations of galactic cosmic rays on the basis of the data of stratospheric measurements. Assuming $\Lambda \sim R^{\alpha}$ (for protons with $R > 1$ Gv), it was shown that $\alpha \approx 0.5$ during 1959-63, $\alpha \approx 1.0$ in the first half of 1964 and $\alpha \approx 0$ in 1965.

The dependence Λ (ε_k) was also studied by Krimigis [28] on the basis of the data on September 28, 1961 flare. It was shown that $\Lambda \approx 10^{12}$ cm = const for energies from 500 Mev up to a few tens of Mev and that it quickly increases on decreasing the energy (Fig. 14.6). This increase contradicts the results of all the works discussed above. The effect mentioned in [28] can be obtained only if the Larmorov radius is taken as the dimension of irregularity. However, transfer together with the moving irregularity becomes significant for particles having such a value of ρ .

According to the estimate of A.I. Kuz'min and G.F. Krymskii [74], who considered the dependence Λ (R) $\sim R^{\alpha}$ on the basis of the data on February 23, 1956 flare, value of α lies in the range 1.8-2.4. Such a value of α does not contradict the assumption about scattering of solar particles on magnetic irregularities of dimensions $l \ll \rho$. In this case,

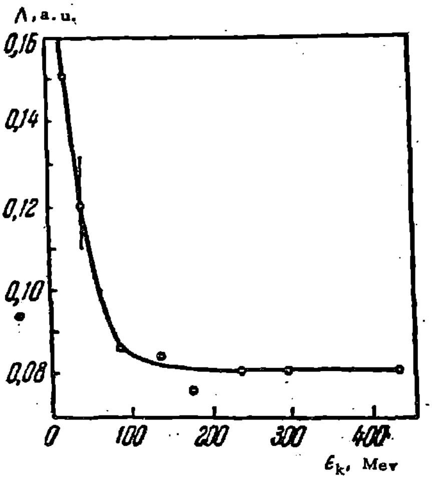

Fig. 14.6. Dependence $\Lambda(\mathcal{E})$ *according to [28].*

in accordance with the formula (13.8), $\alpha = 2$. However, it should be mentioned that the spectrum of direct beam of solar protons in the form $R^{-3.4}$, obtained by Pfotzer [I.45], was used in [74] as the spectrum of the source. It will be shown in Section 14.7 that the spectrum of source for this flare was in fact much softer and the dependence of Λ on R is described by the relation $\Lambda \sim R^{1.0}$. The value $\alpha = 0.7$-0.8 was obtained for the February 23, 1956 flare in the work of A. N. Charakhch'yan and T. N. Charakhch'yan [71].

Thus, all the available experimental data on the dependence $\Lambda(R)$ apparently satisfy the relation $\Lambda \sim R^{\alpha}$ where $0 \lesssim \alpha \lesssim 1$.

Let us consider one more significant aspect. Calculations of L. I. Dorman [I.2], L. I. Dorman and Yu. G. Nosov [17] and of Parker [19] show that scattering at magnetic irregularities must lead to a strong dependence of Λ on the rigidity of particles R. For example, if it is assumed that there is a group of irregularities in the interplanetary space with dimensions ranging between l_1 and l_2, Λ will be defined by the expression (13.8). If the irregular field has the form H_s = const in a circle of radius r (plane problem), scattering of particles of relativistic as well as nonrelativistic energies will be described by the range $\Lambda \sim R^2/H_s$. In case $H_s \sim r^{-3}$ (dipole field), we get the dependence $\Lambda \sim R^{0.5}/H_s$ [17]. Exponential dependence of scattering on rigidity, detected by Parker [19], follows from the assumption of exponential form of the irregular field. If it is assumed that the irregular field decreases according to the law $\sim r^{-3}$, curve of the dependence of scattering amplitude on rigidity will be broader than the exponential curve. Moreover, analysis of measurement data on interplanetary magnetic field shows [20] that the magnetic irregularities are very diverse in dimensions. Therefore, the assumption of Fibich and Abraham [44] that the wide spectrum of irregularities in terms of dimensions together with the wide curves of the dependence of scattering amplitude on R can lead to absolute "smearing" of every dependence of Λ on R, at least in the region of energies measured on satellites (10^6-10^9 ev), is not baseless.

Taking into consideration constancy of Λ in the range $\mathcal{E}_k$ = 10-500 Mev, it is possible to determine the dimension ℓ of magnetic irregularities, distance d between them and the intensity H_s of the field. As shown in Section 13.3, at $\rho \lesssim 1$, the mean free path of particles before colliding with the irregularities is equal to the transport range for diffusion which in this case does not depend on R. Let us, for example, put $\Lambda = 7\text{x}10^{11}$ cm and consider diffusion of protons with $\mathcal{E}_k$ = 500 Mev. Considering that the relations $\Lambda < \ell$ and ρ (500) $\leq \ell$ are valid at $\ell \ll d$, we get the intensity of field at irregularities $H_s > 5\text{x}10^{-6}$ gauss. If $\ell = d$, it is obvious that $\Lambda \sim \ell$ and $\rho \sim \ell \sim \Lambda$ Actually, if the condition $\rho(500) < \ell$ is satisfied, constancy of Λ will be disturbed at $\mathcal{E}_k > 500$ Mev for which $\rho(\mathcal{E}_*) \sim \ell$. Results given in [48] refer to the range $\mathcal{E}_k$ = 10-500 Mev and therefore, it is impossible to observe the above-mentioned effect for September 28, 1961 flare. Therefore, the lower limit of the intensity of field at irregularities $H_s \sim 5\text{x}10^{-6}$ gauss.

There is another approach to the problem of irregularities of magnetic field in the interplanetary space. On the basis of measurements taken with the help of "Mariner-2" [III. 118], it is apparently possible to assume that $H_s = 10^{-5} - 10^{-4}$ gauss. If it is so, the assumption that ℓ=d should be immediately eliminated since in this case $H_s = 5\text{x}10^{-6}$ gauss. The only possible case is when $\ell < d$. At $H_s = 10^{-4} - 10^{-5}$ gauss, we get $\ell \sim \rho(500) \sim 4\text{x}10^{10}$ - $4\text{x}10^{11}$ cm. If the value of ρ for protons with $\mathcal{E}_k$ = 100 Mev is used, the above-mentioned values change by about two times: $\ell \sim \rho(100) \sim 2\times10^{10} - 2\times10^{11}$ cm. It follows from the assumptions made while deriving (13.1) and by considering the constancy of Λ in the range $\mathcal{E}_k$ = 10-500 Mev that the average distance between irregularities $d \sim (\Lambda \ell)^{1/2} \sim (2-5)\times10^{11}$ cm at $\Lambda = 7\times10^{11}$ cm and $\ell = 4\times10^{10} - 4\times10^{11}$ cm. Thus, if the intensity of irregular field $H_s = 10^{-5} - 10^{-4}$ gauss, the condition $\ell < d$ (or even $\ell \ll d$) is fulfilled satisfactorily.

The results thus obtained open interesting possibilities for interpretation. Firstly, in accordance with (13.8), non-dependence of Λ on rigidity of particles with energies up to 500 Mev means that there are irregularities with some minimum size ℓ_1 in the interplanetary space. Secondly, constancy of Λ and large distances between irregularities satisfy the assumption that the irregularities have very abrupt boundary (otherwise, the particles of low rigidity would have started "feeling" the field of irregularities earlier and would have led to significant dependence of Λ on R). Such a conclusion contradicts the hypothesis of E. I. Mogilevskii [12] about the existence of plasma clouds in the interplanetary space whose magnetic field has forceless structure and can be represented by dipole field ($H \sim r^{-3}$) at large distances from the center of the cloud. Actually, in this case $\Lambda \sim R^{0.5} \neq$ const [17] for particles of any energy. As mentioned in Section 13.3, scattering of particles by fields $H_s \sim r^{-n}$ is possible only at $n > 1$. Results obtained in this Section can point out that the irregular field changes with distance according to the law $\sim r^{-n}$ where $n > 3$*.

Similar results on the dependence $\Lambda(\mathcal{E})$ for the same energy range were obtained by Krimigis [28] from the data given in [I.23]. In particular, dimension of irregularity with a field of about $4\gamma = 4 \times 10^{5}$ gauss was found to be equal to $\ell_1 = 9 \cdot 10^{10}$ cm. If it is considered that the value $\ell_1 = 4\times10^{10}$ cm was obtained in [64] for the field $H_s \sim 10^{-4}$ gauss $\approx 10\gamma$, conformity in the values of ℓ_1 can be observed.

A very interesting investigation on the relation between the phase of solar cycle and scattering properties of the

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**It should be mentioned that the relation between Λ and parameters of the interplanetary field is not singular since the mechanism of scattering of particles as well as configuration of the field are not known properly.*

irregularities of the interplanetary field was conducted by McCracken and Rao [75]. The authors [75] based their studies upon the assumption of Parker [76] and Axford [77] that the cosmic particles for which $\rho \ll \ell$ will rotate along with the Sun. If the width of sectors with an arc of about 90° in the ecliptic plane at the Earth's orbit is taken as the value of ℓ [III. 135], i.e., $\ell \approx$ 1.54 a.u., rotation will be observed for particles with $R < 150$ Gv. It must lead to anisotropy of cosmic rays at the Earth's orbit. According to the analysis [75] for the period 1957-65, the observed average solar day anisotropy of cosmic particles with rigidities of 1-100 Gv is in agreement with the above-mentioned theory of joint rotation. Basing on the fact that anisotropy practically remains constant during this period, the authors [75] arrive at the conclusion that frequency of appearance and characteristics of magnetic irregularities with dimensions of 10^{-3} to 10^{-1} a.u. at a distance of 1 a.u. from the Sun approximately do not depend on the phase of solar cycle. Thus, the results of McCracken and Rao [75] impose certain limitations on the mechanisms suggested for explaining the turbulent nature of solar plasma.

Information on irregularities of plasma and field of dimensions less than 10^{-3} a.u. can be obtained from the observations on scintillation of cosmic radio sources. On the basis of observations on scattering of cosmic radio emission near the Sun, V.V. Vitkevich [78, 79] observed a scattering region near the Sun consisting of irregularities of magnetic field. According to V.V. Vitkevich and B.N. Panovkin [80], electron irregularities, observed during eclipse of the Crab nebula by supercorona of the Sun, mainly extend in the radial direction. According to the data of Erickson [81], this effect was observed right up to distances of 0.2 a.u. from the Sun.

One of the last results on the observation of scintillation of radio sources was obtained by Hewish [82]. The observations were made with the help of three radiotelescopes situated at a distance of 50-90 km from each other. It was shown that the variations of plasma density have characteristic dimension of 300-400 km at a distance of 0.8 a.u. from the Sun. Drifting motion of diffraction pattern shows that the irregularities are taken away from the Sun at a velocity of 200-400 km/sec.

New data on the small-scale irregularities of the magnetic field of the Sun and interplanetary plasma are given in the work of V. K. Vitkevich and N. A. Lotova [83].

During February-June 1966, Denisson and Hewish [132] took measurements on the intensity and velocity of solar wind with the help of three antennas of radiotelescope at Cambridge at a frequency of 81.5 MHz. It was found that the velocity of wind from polar regions of solar atmosphere is much more than that in the ecliptic plane (this conclusion was drawn on the basis of observations on the source 3C48 and the radio source in the Crab nebula). It was shown that the dimensions of electron irregularities slightly increase with an increase of heliocentral distance.

In the end of this Section, it should be mentioned that the possible change in the energy of particles during their propagation has not been taken into consideration in the diffusion model under reference, i.e, it was assumed that $|v|$ = const. The obtained values of $\varkappa$ and t are average values for some diffusion volume during the measurement period. It is also obvious that the assumption put forward by some research workers (see, for example, the work of Bennet [126] about the dependence of average $\varkappa$ on t (during observations on a specific flare at the same station) is actually another formulation of the dependence of $\varkappa$ on the energy of particles.

14.5 Dependence of diffusion coefficient on the degree of solar activity. Accordong to numerous data on the observation on solar cosmic rays, the transport range for diffusion hardly depends on time during the cycle of solar activity. It is in agreement with the results obtained by McCracken and Rao [175] from the analysis of daily anisotropy of cosmic rays during 1957-65. It should however be expected from general considerations of the change in the degree of disturbances in the interplanetary medium during solar cycle that diffusion coefficient (transport range) will, with the passage of time, change its dependence on the energy of particles and distance from the Sun. In this connection, the indications on the possible dependence of $\varkappa$ on the degree of solar activity, obtained by A. N. Charakhch'yan et al. [84], are of great interest (also see the work of A. N. Charakhch'yan and T. N. Charakhch'yan [85].

According to [84], solar cosmic rays, apparently generated by two class 3^+ chromospheric flares (at 2351 UT on September 20 and at 0710 UT on September 26, 1963 respectively) in the region with heliocoordinates 11°N and 9°W, were recorded in stratosphere over Murmansk and simultaneously over Mirny (Antarctica) on September 21 and 26, 1963. Differential energy spectra of protons for these flares were practically the same and the index in the energy range of 120-200 Mev was approximately equal to 4.6, i.e., it hardly differs from that measured by A. N. Charakhch'yan and T. N. Charakhch'yan [III. 94] during the July 12, 1961 flare. It should be mentioned that at proton energies $\mathcal{E}_k < 100$ Mev for September 21, 1963 flare, the index of spectrum, according to the data of Pfotzer et al. [86] is close to $\gamma = 3.0$.

Low degree of solar activity is a significant peculiarity of the period September 21-26, 1963. Although the data obtained by A. N. Charakhch'yan [84] are very scanty, a comparison with other flares shows that the value of $\varkappa$ in September 1963 was more than the values obtained earlier in the same energy range. The specific tendency of diffusion coefficient to increase with a decrease in solar activity was observed.

Time dependences of the number of primary protons are shown in Fig. 14.7 for the following flares: May 4, 1960 from the measurement data of A. N. Charakhch'yan et al. [613] for protons with $\mathcal{E}_k > 100$ Mev (curve 1); July 20, 1961 from the data of Hofmann and Winckler [III. 88] over Churchill for the same energies (curve 2); October 23, 1962 from the measurement data of Bryant et al. [I. 54] on "Explorer-14" for protons with $\mathcal{E}_k = 130$ Mev (curve 3); September 26, 1963 from the data of A. N. Charakhch'yan et al. [84] (curve 4). Time from the commencement of chromospheric flare is taken along the abscissa and intensity in arbitrary units, along the ordinate. The data were processed in such a way that the number of particles at the maximum of each flare was the same. There are two measurements for the September 26, 1963 flare -- one measurement was taken 0.8 hours after the chromospheric flare and the second, after 9 hours (squares in Fig. 14.7). The first point for t = 0.8 hours on September 26, 1963 flare coincides with curve 1 along the ordinate. Position of the experimental point for t = 9 hours which lies considerably below the ordinates of curve 1-3 is determined by this standardization.

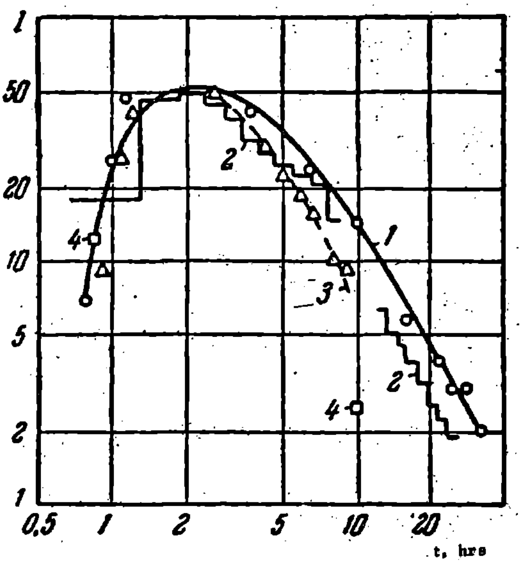

Fig. 14. 7. Time variation of solar protons for the flares of May 4, 1960 (1); July 20, 1961 (2); October 23, 1962 (3) and September 26, 1963 (4) [84].

A rapid fall of time dependences for later flares after the maximum is obvious from Fig. 14.7 which can indicate an increase in $\varkappa$ with a decrease in the activity of the Sun. Increase in $\varkappa$ is equivalent to a decrease in time scale t. Shifting the measurement data towards right till they coincide with the ordinate of curve 1, i.e., comparing them with the data on May 4, 1960 flare, we find the increase of diffusion coefficients for 1961, 1962 and 1963 as compared to May 4, 1960 flare for which $\varkappa \sim 5.5 \times 10^{21}$ cm^2/sec [63]. Results of this procedure are given in Table 14.3 in which total activity of the Sun is

TABLE 14.3

Change in $\varkappa$ with the cycle of solar activity

Date of flare	$\varkappa$, cm^2/sec	n
May 4, 1960	5.5×10^{21}	266
July 20, 1961	6.5×10^{21}	152
October 23, 1962	8.0×10^{22}	94
Septmber 26, 1963	1.5×10^{22}	68

characterized by the total number of groups of sunspots observed during the months May 1960, July 1961, October 1962 and September 1963. Basing on the data of Table 14.3, it is possible to find an approximate dependence of $\varkappa$ on n. If represented as a power function $\varkappa \sim n^k$ we get $k = 0.5$ by using the first three results of the Table and $k \approx 0.75$ on using the data on May 4, 1960 and September 26, 1963 flares.

14.6 Dependence of diffusion coefficient on distance from the Sun.

Preliminary estimates. Dimension of magnetic irregularities, average distance between them and the intensity of field in them apparently depend on the distance from the Sun. Therefore, L.I. Dorman [III.111] assumed that the transport range for diffusion will increase with the increase in r.

Preliminary estimates of the dependence $\Lambda(r)$ were made in the work of L.I. Dorman and L.I. Miroshnichenko [64] on the basis of the data on September 28, 1961 flare. As follows from (14.7), decrease in the intensity of solar particles after attaining maximum is mainly defined by the factor $(\varkappa t)^{-3/2} \sim (\Lambda v t)^{-3/2}$. The law describing the decrease in the intensity can be represented in the form $\sim t^{-s} \sim (\Lambda v t)^{-3/2}$. If Λ is a function of r, this dependence will determine the value of index s of the power law. Actually, considering in the diffusion theory the distance covered as related to time by the relation $t \sim r^2/\Lambda v$, we get $(\Lambda v r^2/\Lambda v)^{-3/2} \sim (r/\Lambda v)^{-s}$ from where $\Lambda v \;\; r^{2-3/s}$ or $\Lambda \sim r^{2-3/s}$ (for particles of a given velocity $|v| = \text{const}$). If $s = 3/2$, $\Lambda = \text{const}$ which corresponds to the elementary diffusion model.

It can be seen from Fig. 14.4 that time variation of the intensity of particles with $\mathcal{E}_k \lesssim 30$ Mev is satisfactorily described by the usual diffusion curve with $\Lambda = \text{const}$ at least within the limits of that interval of time for which experimental data are available. Decrease in the intensity of particles with $\mathcal{E}_k \gtrsim 100$ Mev was quicker while the index of the power law was within the limits $2 \leq s < 3$ (this uncertainity was caused by large experimental errors at the end of the event). These results make it possible to draw the preliminary conclusion [64] that, for explaining the deviations from the law $\sim t^{-3/2}$ it is not necessary to assume that there are certain limitations on the diffusion region (see Section 14.3) but it is sufficient to assume the presence of a comparatively weak dependence $\Lambda(r) \sim r^{\beta}$ where $\beta = 2-3/s$ increases from 0 to 1 on increasing the energy of particles from a few tens of Mev to hundreds of Mev. It should be pointed out that at $\mathcal{E}_k \lesssim 30$ Mev, the conclusion about nondependence of Λ on r ($\beta = 0$) is not very definite due to absence of corresponding data at the final stage of September 28, 1961 flare.

It is appropriate to mention that the other possible cause for the violation of law $\sim t^{-3/2}$, i.e., additional convectional transfer of particles due to directed radial movement of magnetic irregularities from the Sun, apparently does not play a significant role for the flare under reference. According to estimates of L. I. Dorman and L. I. Miroshnichenko [87], this effect for particles of above-mentioned energies must appear at the Earth's orbit at $t > 10^5$ sec after solar flare. In this case, it was difficult to observe this effect since Forbush effect started at $t = 1.65 \times 10^5$ sec after the flare.

In view of the importance of the problem of the dependence $\Lambda(r)$, a number of research workers made attempts to analyze it from more general aspects than it was done in [64].

Solution of generalized diffusion equation. Krimigis [28] made an attempt to partially generalize the isotropic diffusion model by basing upon following assumptions: a) the particles diffuse owing to casual wandering in the medium from static scattering centers; b) isotropic scattering; c) particles neither gain nor lose energy in the process of scattering; d) density of scattering centers decreases on increasing the radial distance r from the Sun but does not depend on the heliographic longitude and latitude. This type of model was for the first time studied by Parker [I.61].

In order to get a correct solution of differential equation, it is necessary to assume a definite dependence of diffusion coefficient on the coordinates. Following Parker, let us assume that diffusion coefficient depends on r according to a power law, i.e., $\varkappa = \varkappa_з (r/r_з)^\beta$ where β and $\varkappa$ are parameters not depending on r but possibly depending on the energy of particles. Then, the diffusion equation has the form.

$$\frac{\partial n}{\partial t} = \frac{1}{r^\sigma} \frac{\partial}{\partial r}\left(M r^{\sigma+\beta} \frac{\partial n}{\partial r}\right). \tag{14.27}$$

Here $M = \varkappa / r_з^\beta$ and σ is a parameter defining the extent of diffusion process (σ = 0 -- two dimensional diffusion; σ = 1 -- one-dimensional diffusion; σ = 2-- three-dimensional diffusion and $\sigma > 2$ -- diffusion in a pipe-shaped region). Parker obtained the solution of this equation without any computations [I. 61]. Considering that the detailed solution may be of some interest, let us derive it with usual modifications as applicable to propagation of particles.

Let us write the expression (14. 27) in the form

$$\frac{\partial n}{\partial t} = \frac{1}{r^\sigma} \frac{\partial}{\partial r}\left[M r^\sigma r^\beta \frac{\partial n}{\partial r}\right]. \tag{14.28}$$

The boundary conditions lead to the fact that n must be equal to zero at infinity. Let us put τ = Mt. Then

$$\frac{\partial n}{\partial \tau} = r^{-\sigma} \frac{\partial}{\partial r}\left(r^{\sigma+\beta} \frac{\partial n}{\partial r}\right) \tag{14.29}$$

or after differentiating

$$\frac{\partial n}{\partial \tau} = r^\beta \frac{\partial^2 n}{\partial r^2} + (\sigma + \beta) r^{\beta-1} \frac{\partial n}{\partial r}. \tag{14.30}$$

We will search for the solution in the form

$$n(r, \tau) = R(r) T(\tau). \tag{14.31}$$

Putting the parameters in (14.30) appropriately, we get

$$\frac{1}{T} \cdot \frac{\partial T}{\partial \tau} = \frac{r^\beta}{R} \frac{\partial^2 R}{\partial r^2} + (\sigma + \beta) r^{\beta-1} \frac{1}{R} \frac{\partial R}{\partial r}.$$

Since each part of the equation is a function of only one variable,, it can be written as

$$\frac{1}{T} \frac{\partial T}{\partial \tau} = \frac{r^\beta}{R} \frac{\partial^2 R}{\partial r^2} + (\sigma + \beta) r^{\beta-1} \frac{1}{R} \frac{\partial R}{\partial r} = -k^2,$$

where $-k^2$ is a constant. It directly follows from this that

$$\frac{1}{T}\frac{\partial T}{\partial \tau}=-k^2, \qquad T=e^{-k^2\tau}. \tag{14.32}$$

Let us now consider the equation

$$r^{\beta}\frac{d^2R}{dr^2}+(\sigma+\beta)r^{\beta-1}\frac{dR}{dr}+k^2R=0$$

or

$$\frac{d^2R}{dr^2}+\frac{\sigma+\beta}{r}\frac{dR}{dr}+\frac{k^2}{r^{\beta}}R=0. \tag{14.33}$$

Solution of this equation is expressed in terms of modified functions of Bessel and satisfies the following relation:

$$R(r)=\frac{1}{r^{(\sigma+\beta-1)/2}}J_p\left[\frac{2k}{(\beta-2)\,r^{(\beta-2)/2}}\right], \tag{14.34}$$

where $p = (\sigma + \beta + 1)/(2-\beta)$.

The complete solution is the superposition of functions (14.32) and (14.34):

$$n(r,\tau)=\frac{1}{r^{(\sigma+\beta-1)/2}}\int_0^{\infty}dk\cdot kf(k)\exp(-k^2\tau)J_p\left[\frac{2k}{(\beta-2)}\frac{1}{r^{(\beta-2)/2}}\right]. \tag{14.35}$$

At $\tau = 0$, 23 get

$$n(r,0)=\frac{1}{r^{(\sigma+\beta-1)/2}}\int_0^{\infty}dk\cdot kf(k)J_p\left[\frac{2k}{\beta-2}\frac{1}{r^{(\beta-2)/2}}\right]$$

or

$$r^{(\sigma+\beta-1)/2}\cdot n(r,0)=\int_0^{\infty}dk\cdot kf(k)J_p\left[\frac{2k}{\beta-2}\frac{1}{r^{(\beta-2)/2}}\right]. \tag{14.36}$$

In order to express f(k) in terms of n (r, o), it is possible to use the theorem of Fourier-Bessel transformation:

$$\Phi(r)=\int_0^{\infty}kf(k)J_{\gamma}(kr)\,dk, \tag{14.37}$$

$$f(k)=\int_0^{\infty}r\Phi(r)J_{\gamma}(kr)\,dr. \tag{14.38}$$

After algebraic transformations, we get

$$f(k)=\frac{2}{2-\beta}\int_0^{\infty} dr\cdot r^{(\sigma-\beta+1)/2} J_p\left[\frac{2k}{\beta-2}\,\frac{1}{r^{(\beta-2)/2}}\right] n(r,\,0). \qquad (14.39)$$

If N particles per unit solid angle are emitted at t = .0, then n (r, o) can be written as

$$n(r,\,0)=\lim_{\varepsilon\to 0} N\,\frac{\delta(r-\varepsilon)}{\varepsilon^{\sigma}}. \qquad (14.40)$$

Now, we have

$$(k)=\lim_{\varepsilon\to 0}\frac{2}{2-\beta}\int_0^{\infty}\frac{r^{(\sigma-\beta+1)/2}}{\varepsilon^{\sigma}} J_p\left[\frac{2k}{(\beta-2)}\,\frac{1}{r^{(\beta-2)/2}}\right] N\delta(r-\varepsilon)\,dr=$$

$$=\lim_{\varepsilon\to 0}\frac{2N}{2-\beta}\,\varepsilon^{(1-\sigma-\beta)/2}\left[\frac{2k}{2(\beta-2)}\,\frac{1}{\varepsilon^{(\beta-2)/2}}\right]\times$$

$$\times\sum_{j=0}^{\infty}\frac{(-1)^j}{j!\,\Gamma\left(j+\frac{\sigma+\beta-1}{2-\beta}+1\right)}\left(\frac{2k}{(\beta-2)\,\varepsilon^{(\beta-2)/2}}\right)^{2j}, \qquad (14.41)$$

where definition of Bessel's function has been used. Expanding the formula (14.41), we get

$$f(k)=\frac{2N}{2-\beta}\lim_{\varepsilon\to 0}\varepsilon^{(1-\sigma-\beta)/2+\frac{1}{2}(\sigma+\beta-1)}\left(\frac{k}{\beta-2}\right)^{(\sigma+\beta-1)/(2-\beta)}\times$$

$$\times\left[\frac{1}{\Gamma\left(1+\frac{\sigma+\beta-1}{2-\beta}\right)}-\frac{1}{\Gamma\left(1+\frac{\sigma+\beta-1}{2-\beta}+1\right)}\left(\frac{2k}{\beta-2}\right)^2\varepsilon^{-\beta+2}+\right.$$

$$\left.+\,\mathrm{const}\,\varepsilon^{2(-\beta+2)}+\ldots\right]=\frac{2N}{2-\beta}\lim_{\varepsilon\to 0}\varepsilon^{0}\left(\frac{k}{\beta-2}\right)^{(\sigma+\beta-1)/(2-\beta)}\times$$

$$\times\left[\frac{1}{\Gamma\left(1+\frac{\sigma+\beta-1}{2-\beta}\right)}-\frac{1}{\Gamma\left(1+\frac{\sigma+\beta-1}{2-\beta}+1\right)}\left(\frac{2k}{\beta-2}\right)^2\varepsilon^{-\beta+2}+\right.$$

$$\left.+\,\mathrm{const}\,\varepsilon^{2(-\beta+2)}+\ldots\right].$$

It is obvious from the last expression that, when $\varepsilon \to 0$, it is necessary to confine ourselves to the values $\beta < 2$ as otherwise this expression becomes indefinite. Putting $\beta < 2$, we finally get

$$f(k) = \frac{2N}{2-\beta}\left(\frac{k}{\beta-2}\right)^{(\sigma+\beta-1)/(2-\beta)} \frac{1}{\Gamma\left(\frac{\sigma+1}{2-\beta}\right)} \tag{14.42}$$

Now let us put (14.42) in (14.35):

$$n(r, \tau) = \frac{1}{r^{(\sigma+\beta-1)/2}} \int_0^\infty dk \cdot k \frac{2N'}{2-\beta}\left(\frac{k}{\beta-2}\right)^{(\sigma+\beta-1)/(2-\beta)} \times$$

$$\times \frac{1}{\Gamma[(\sigma+1)/(2-\beta)]} \exp(-k^2\tau) J_p\left[\frac{2k}{(\beta-2)} \frac{1}{r^{(\beta-2)/2}}\right] =$$

$$= \frac{2N}{2-\beta} \frac{1}{\Gamma[(\sigma+1)/(2-\beta)]} \frac{1}{(\beta-2)^{(\sigma+\beta-1)/(2-\beta)}} \frac{1}{r^{(\sigma+\beta-1)/2}} \times$$

$$\times \int_0^\infty dk \cdot k^{(\sigma+\beta-1)/(2-\beta)+1} J_0\left[\frac{2k}{(\beta-2)} \frac{1}{r^{(\beta-2)/2}}\right] \exp(-k^2\tau).$$

Integral in this general form can be evluated as

$$\int_0^\infty J_\nu(at) \exp(-n^2\tau^2)\, t^{\nu+1}\, dt = \frac{a^\nu}{(2p^2)^{\nu+1}} \exp\left(-\frac{a^2}{4p^2}\right).$$

Consequently

$$n(r, t) = \frac{N}{(2-\beta)^{(2\sigma+\beta)/(2-\beta)}} \frac{1}{\Gamma[(\sigma+1)/(2-\beta)]} \frac{1}{\tau^{(\sigma+1)/(2-\beta)}} \times$$

$$\times \exp\left(-\frac{r^{2-\beta}}{(2-\beta)^2\tau}\right).$$

Putting Mt in place of τ, we finally get

$$n(r, t) = \frac{N}{(2-\beta)^{(2\sigma+\beta)/(2-\beta)}} \frac{r_{♁}^{\beta(\sigma+1)/(2-\beta)}}{\Gamma[(\sigma+1)/(2-\beta)]} \left(\frac{1}{\varkappa_{♁}}\right)^{(\sigma+1)/(2-\beta)} \times$$

$$\times \frac{1}{t^{(\sigma+1)/(2-\beta)}} \exp\left(-\frac{r_{♁}^\beta}{\varkappa_{♁}} \frac{r^{2-\beta}}{(2-\beta)^2} \frac{1}{t}\right) \tag{14.43}$$

This is the required solution of equation (14.27). To verify if it gets a simpler form in special cases, let us put $\sigma =$ = 2 (spherical geometry) and $\beta = 0$ (usual diffusion with constant $\varkappa_{\text{♁}}$). Then (14.43) takes the form:

$$n(r, t) = \frac{N}{2^2 \Gamma(3/2)} \frac{1}{(\varkappa_{\text{♁}} t)^{3/2}} \exp\left(-\frac{r^2}{4\varkappa_{\text{♁}} t}\right) = $$

$$= \frac{N}{2\pi^{1/2} (\varkappa_{\text{♁}} t)^{3/2}} \exp\left(-\frac{r^2}{4\varkappa_{\text{♁}} t}\right).$$

It is simple to find the solution of diffusion equation with constant diffusion coefficient $\varkappa$ in the expression for infinite medium.

For change-over from (14.43) to observation data, let us use the relation $n = 4\pi I/v$ where I is the directional intensity and is the velocity of particles. In this expression, it is unambiguously assumed that the intensity is isotropic. The equation (14.43), valid only for particles of a definite energy, takes the form

$$I(r, t) = \frac{N v r_{\text{♁}}^{\beta(\sigma+1)/(2-\beta)}}{4\pi (2-\beta)^{(2\sigma+\beta)/(2-\beta)} \Gamma[(\sigma+1)/(2-\beta)]} \times$$

$$\times \frac{1}{t^{(\sigma+1)/(2-\beta)}} \left(\frac{1}{\varkappa_{\text{♁}}}\right)^{(\sigma+1)/(2-\beta)} \exp\left[-\frac{r_{\text{♁}}^{\beta}}{\varkappa_{\text{♁}}} \frac{r^{2-\beta}}{(2-\beta)^2} \frac{1}{t}\right]. \quad (14.44)$$

Multiplying the left and right-hand sides of (14.44) by $t^{(\sigma+1)(2-\beta)}$ and taking the logarithms, we get

$$\ln I t^{(\sigma+1)/(2-\beta)} = \ln\left[\frac{N v r_{\text{♁}}^{\beta(\alpha+1)/(2-\beta)}}{(2-\beta)^{(2\alpha+\beta)/(2-\beta)} \Gamma[(\alpha+1)/(2-\beta)]} \times \right.$$

$$\left. \times \left(\frac{1}{\varkappa_{\text{♁}}}\right)^{(\sigma+1)/(2-\beta)}\right] - \frac{r_{\text{♁}}^2}{\varkappa_{\text{♁}} (2-\beta)^2} \frac{1}{t}. \quad (14.45)$$

If the graph of the dependence of $\ln I t^{(\sigma+1)(2-\beta)}$ on t^{-1} is now plotted, we get a set of straight lines corresponding to different values of the index $s = (\sigma + 1)/(2-\beta)$. Inclination of a specific straight line is determined from the relation

$$m = -\frac{r_{\delta}^{2}}{(2-\beta)^{2}\varkappa_{\delta}}. \tag{14.46}$$

The point of interesection of straight line with t^{-1} axis at $t = \infty$ gives the value

$$b = \ln\left[\frac{N v r_{\delta}^{3(\sigma+1)/(2-\beta)}}{(2-\beta)^{(2\sigma+\beta)/(2-\beta)}\,\Gamma[(\sigma+1)(2-\beta)]}\left(\frac{1}{\varkappa_{\delta}}\right)^{(\sigma+1)/(2-\beta)}\right] \tag{14.47}$$

Differentiating (14.44) with respect to t and putting the derivative equal to zero, we get the time of maximum intensity:

$$t_{\max} = \frac{1}{\varkappa_{\delta}}\,\frac{r_{\delta}^{2}}{(2-\beta)^{2}(\sigma+1)}. \tag{14.48}$$

These expressions give a complete description of variations of the intensity of solar particles as a function of time and space.

Fig. 14.8, a represents a series of calculated curves showing variations of intensity (in arbitrary units) at different distances from the Sun for the case when $\sigma = 2$, $\beta = 1$. It is seen from (14.44) that the decrease does not take place according to the exponential law although different sections of curves can be approximated by such a law during the periods whose duration is defined by the values r and $\varkappa_{\delta}$. As is seen from Fig. 14.8 a, the decrease at r = 3 or 4 a.u. takes place along the exponent in the interval from 15 to 40 hours. If the graph of calculated intensity is plotted as a function of t on a logarithmic scale (Fig. 14.8, b), it can be seen that, even after 50 hours of the commencement of event, the intensity at r = 1 a.u., does not satisfy the asymptotic law of decrease which in this case has the form $\sim t^{-3}$. It is seen from Fig. 14.8 that the law of decrease of intensity depends on $\varkappa_{\delta}$ and r, as well as on the values of σ and β. Moreover, it should be kept in view that $\varkappa_{\delta}$ and β can depend on the energy of particles. Thus, this comparatively simple model opens new possibilities of interpreting experimental data on flares of solar cosmic rays.

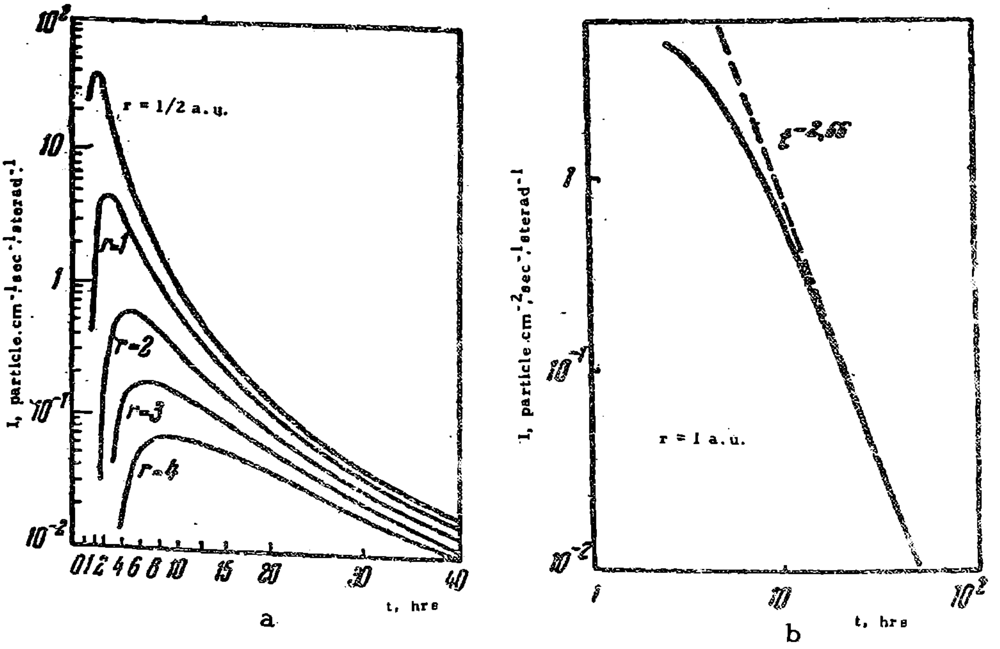

Fig. 14.8. Intensity of monoenergetic beam of particles at different distances from the Sun as a linear (a) and logarithmic (b) function of it.

Dependence of the intensity on the position in space at $\sigma = 2$ and $\beta = 1$ for different instants of time is shown in Fig. 14.9. It is seen that at t = 1 hr, distribution of particles has a sharp peak at the origin while the intensity is almost constant at t = 100 hrs at least up to distances of about 6 a.u. These curves can serve as additional means of interpreting the data, obtained by space probes at various heliocentral distances.

Analysis of observational data. Applicability of the above-mentioned model was verified by Krimigis [28] on the basis of the analysis of a few groups of observational data at r = 1 a.u. It is necessary to mention that if $\varkappa_\pm$ is unknown, observations at one point $r = r_\pm$ cannot give values of σ and β separately. The assumption about the effective geometry of diffusion process is necessary for unambiguous definition of β. In the analysis of Krimgis [28], it was assumed that $\sigma = 2$ and it was taken that the time of emission of solar particles t_0 coincides with the time of outburst of hard X-ray radiation. In the absence of X-ray outburst, the time of beginning of optical flare can be taken as t_0. It should be mentioned that the error of the order

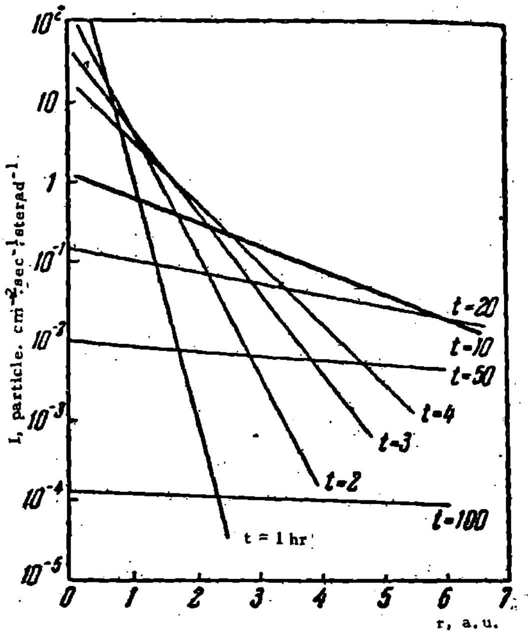

Fig. 14.9 Dependence of the intensity of solar particles on the distance from the Sun at different instants of time.

of 5 minutes in selection of zero moment has an insignificant effect on the values of β and $\varkappa_{\frac{1}{6}}$ determined from the analysis of the data on I as a function of t.

Graph of the dependence of $\ln It^{3/(2-\beta)}$ on t^{-1}, drawn with the help of data [I. 23] on September 28, 1961 flare for different values of β, are shown in Fig. 14.10a. It is seen that better approximation to straight line is achieved at $\beta = 2/3$. It should be mentioned that integral spectra of the intensity of protons of energy $\mathcal{E}_p > 23$ Mev have been used here. The value $\beta = 1$ is more suitable to protons of energy $\mathcal{E}_p \doteq 118$-150 Mev (Fig. 14.10, b).

Similar graphs for protons of energy $\mathcal{E}_k > 40$ Mev for the flares of July 18, 1961 (on the basis of measured data from "Injun-1" [125]) and of July 18 and 20, 1961 (obtained by us from stratospheric data [III. 88]) are shown in Figs. 14.11 and 14.12 respectively. Another case is shown in Fig. 14.13 for April 15, 1963 flare on the basis of the data obtained by Frank [III. 95] with the help of the satellite "Explorer-14" (see

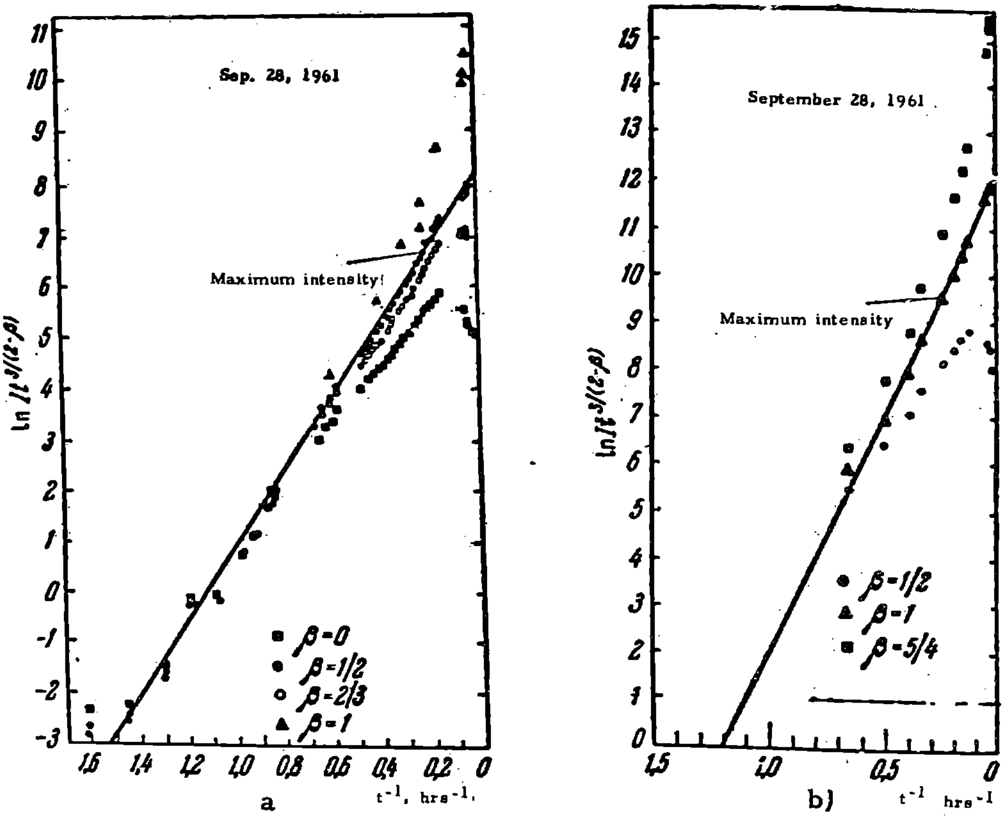

Fig. 14.10. Graphs of the dependence of ln $It^{3(2-\beta)}$ on t^{-1} at different values of β for the september 28, 1961 flare: a) for protons with $\mathcal{E}_p >$ 23 Mev; b) for protons with $\mathcal{E}_p = 118\text{-}150$ Mev.

Section 10). These data conform well to the above-mentioned model at $\beta \leq 1$.

It is seen from the study of these three flares that a satisfactory interpretation of data is possible for close but slightly differing values of β. These variations in the values of β are apparently caused by the changes in the state of the interplanetary medium and possibly by differences in the energy spectra of particles.

Dependence of β and $\mathcal{E}$. To explain this dependence Krimigis [28] used the data on September 28, 1961 flare [I, 23] for different values of the energy of protons. It was found that for different energy ranges, satisfactory conformity

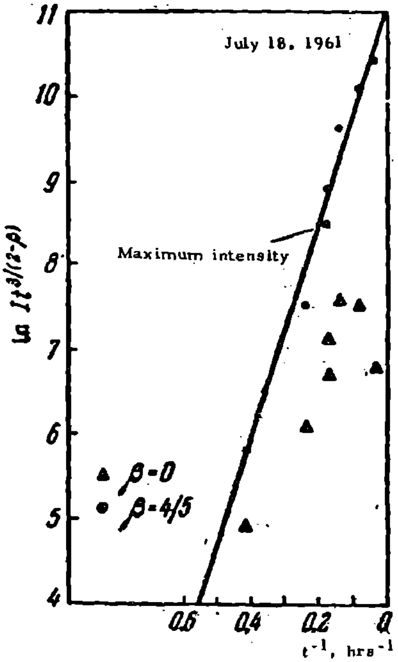

Fig. 14.11. Graphs of the dependence of $\ln It^{3/(2-\beta)}$ *on* t^{-1} *at different values of* β *for July 18, 1961 flare on the basis of the data of satellite measurements for protons with* $\varepsilon_k > 40$ *Mev.*

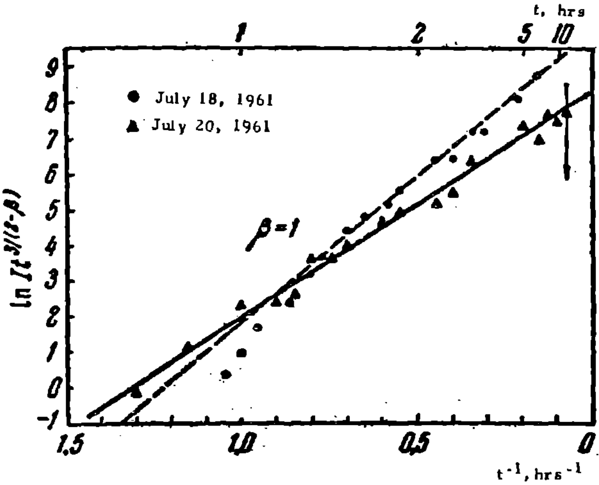

Fig. 14.12. Graphs of the dependence of $\ln It^{3(2-\beta)}$ *on* t^{-1} *at* $\beta = 1$ *for July 18 and 20, 1961 flares on the basis of the data of stratospheric measurements.*

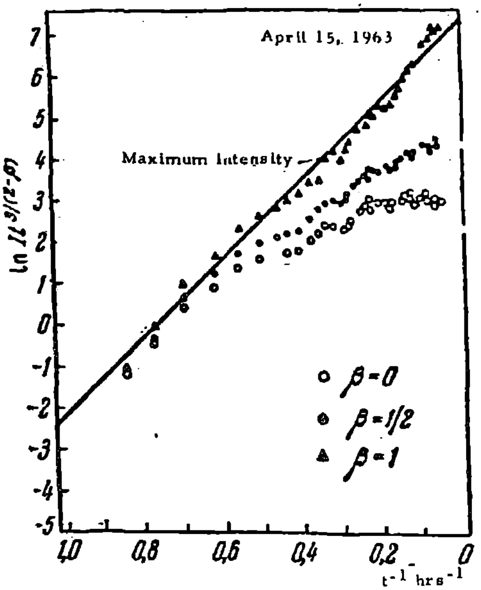

Fig. 14.13. Graphs of the dependence of $\ln It^{3(2-\beta)}$ *on* t^{-1} *at different values of* β *for April 15, 1963 flare for protons with* $\mathcal{E}_p > 23$ *Mev.*

to the above-mentioned model is observed at only one value of β, namely $\beta = 1.0$ (Table 14.4). Dependence of β on $\mathcal{E}$ for September 28, 1961 flare is shown in Fig. 14.14. It is seen that μ does not depend on $\mathcal{E}$ at $\mathcal{E} > 55$ Mev but suddenly falls in the range from 55 to 23 Mev. This result has some uncertainity due to bad quality of data at the final stage of the event. Nevertheless, it can be confirmed that β is slightly more than 2/3 but less than 1.

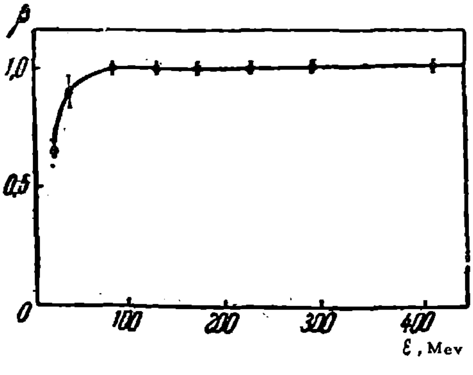

Fig. 14.14. Dependence of β *on the energy of protons for the September 28, 1961 flare.*

TABLE 14.4

Diffusion parameters for nonrelativistic solar protons [28]

Date of flare	$\mathcal{E}_p$, Mev	β for $\sigma = 2$	m	b	$\frac{N}{4\pi}$, $\frac{\text{particle}}{\text{sterad}}$
July 18, 1961	> 40	4/5	-12.4	10.9	5.58×10^{30}
Sept. 28, 1961	> 23	2/3	-7.30	8.30	1.02×10^{30}
	> 40	4/5	-8.38	7.9	-
	55-118	1	-12.0	4.99	2.34×10^{29}
	118-150	1	-10.16	3.99	6.01×10^{28}
	150-200	1	-9.81	3.14	3.98×10^{28}
	200-255	1	-8.58	2.49	3.11×10^{28}
	255-335	1	-7.93	1.44	1.85×10^{28}
	335-500	1	-7.03	0.24	1.47×10^{28}
April 15, 1963	> 23	1	-9.6	7.4	1.59×10^{29}

The problem of the dependence of Λ on r was also analyzed in the work of L. I. Miroshnichenko [44] by considering emission spectrum in the form $\sim R^{-\gamma}$ and for the following different values; $\sigma = 0$-3; $p = 0$-1.5; $\gamma = 0$-7; $r = 1$-4 a. u.; $\varkappa_\delta = 10^{20}$-$10^{23}$ cm^2/sec; $R = 10$-10^4 Mv and $t = 10^3$-10^7 sec.

Results of the calculation of the time variation of concentration are shown in Fig. 14.15. As is seen from (14.44), the values $\beta = 0$; 0.5 and 1 correspond to decrease in concentration with time according to the law $\sim t^{-3/2}$; $\sim t^{-2}$ and t^3 at $t > t_{max}$ and $\sigma = 2$.

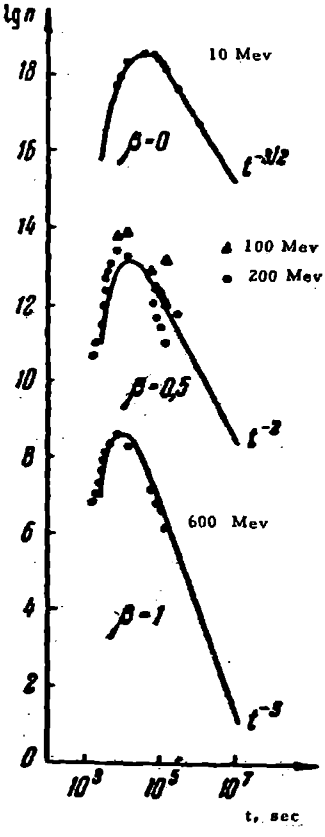

Fig. 14.15. Dependence lgn(t) at different values of β *and for several values of the energy of protons [44].*

Data [I. 23] on September 28, 1961 flare were used for comparison with the experiment by assuming that the time of emission of particles coincided with the commencement of

X-ray outburst. Number of experimental points at large values of t is limited but nevertheless, it can be seen from Fig. 14. 14 in which experimental errors are not more than the dimensions of points, that $\varkappa$ for particles with $\mathcal{E}_k \sim 10$ Mev does not apparently depend on $\varkappa$ (this conclusion is not certain due to absence of data at large values of t) while diffusion coefficient for particles with $\mathcal{E}_k \geqslant 100$ Mev increases on increasing the distance from the Sun approximately, according to the law $r^{0.5-1.0}$. These results do not contradict the results obtained in [28, 64] by other methods.

Data [III. 88] on July 18 and 20, 1961 flares were once again analyzed in [44] on the basis of (14. 44). The reason for this verification was the fact that the value $\beta = 3$ was obtained in [III. 88] which contradicts the results of other works. It is seen from Fig. 14.12 that the experimental data on these flares satisfy the value $\beta = 1.0$ within the limits of errors. In the same way, L. I. Miroshnichenko [88] analyzed the data of many neutron monitors on February 23, 1956 flare. The dependence of $\ln It^{3/(2-\beta)}$ on t^{-1} for different values of β is shown in Fig. 14. 16. It is seen that the data of Ottawa station ($R_{min} = 1.05$ Gv)

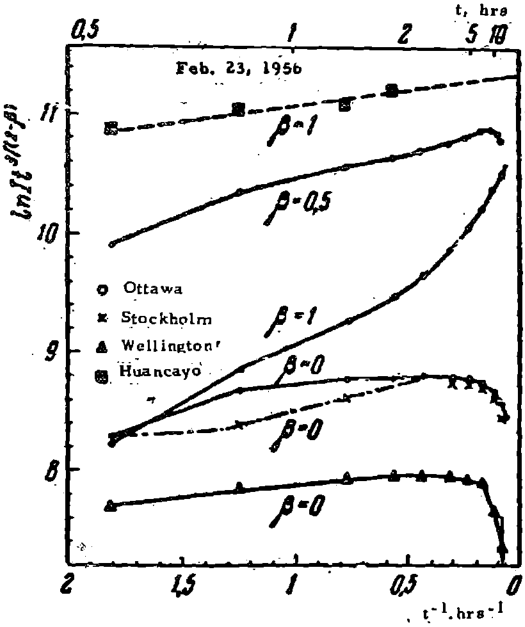

Fig. 14. 16. Observation data on February 23, 1956 flare at different values of β.

satisfy the value $\beta = 0.5$ everywhere excepting last points corresponding to large values of t after the commencement of the outburst. Curves of the dependence of $\ln It^{3/2}$ on t^{-1} for Stockholm and Wellington stations are similar to the corresponding curves for Ottawa station from where it follows that the value $\beta = 0.5$ is valid for all the three stations (in spite of the fact that they are situated in different longitudinal zones). The data for the hill station Huancayo ($R_{min} = 13.7$ Gv) is also given in the same Fig. 14. 16. It is seen that time variation of concentration of particles of high rigidity satisfies $\beta = 1.0$.

Dependence of $\ln It^2$ on t^{-1} for the following six hill stations is plotted in Fig. 14. 17: Cliamax ($R_{min} = 3.08$Gv), Albukerke (4.52 Gv), Sacramento (5.10 Gv), Mexico (10.0 Gv), Nori kura (12.2 Gv) and Hunacayo (13.7 Gv). The threshold rigidities here have been taken in accordance with [I. 33]. On the basis of Fig. 14.17, it can be confirmed that the data of mountainous monitors satisfy the value $\beta = 0.5$ within the limits of experimental errors although the value $\beta = 1.0$ may be suitable for stations having high rigidity as is obvious from Fig. 14. 16 for Huancayo. Thus, it can be assumed that the data of neutron component for the February 23, 1956 flare are fully described by the dependence $\varkappa \sim r^{\beta}$ where $0.5 \lesssim \beta \lesssim 10$.

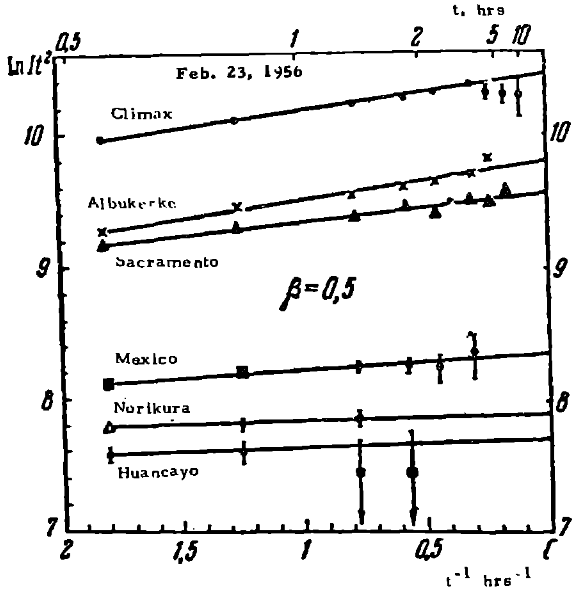

Fig. 14. 17. Data of high-altitude stations on February 23, 1956 flare at $\beta = 0.5$.

The dependence $\varkappa(r)$ was also studied by Parker [I. 61], G.F. Krymskii [89], A.N. Charakhch'yan and T.N. Charakhch'yan [71], Heristchi et al. [III. 107]. While studying the dependence of $\varkappa$ on r for the February 23, 1956 flare, the author [I. 61; 89] arrived at the conclusion that this dependence satisfies the value of β in the range 0.5-1.0.

Data on time dependences of intensity of protons for 15 flares, recorded with balloons in stratosphere and with the help of satellites beyond the limits of magnetosphere, are analyzed in the work of A.N. Charakhch'yan and T.N. Charakhch'yan [71] (Table 14.5). The authors [71] paid attention to the fact that, on assuming $\varkappa=\varkappa_{♁}(r/r_{♁})^{\beta}$, $\beta=0.5$ for seven flares and $\beta=1$ for eight other flares. It is also important to mention that the dependence of diffusion coefficient on r for the same flare was found to be the same for protons of different energies. As shown in [71], two groups of values of β cannot be explained by the difference in the place of generation of cosmic rays on the Sun. It was expected since the values of β in Table 14.5 were mainly found from the decrease of intensity, i.e., the maximum of "diffusion wave" was situated on the Earth's orbit where the effect of radial magnetic fields on propagation of solar particles is generally small.

Dependence of diffusion coefficient on R was also found to be different for different flares. For example, for the flares of September 3, 1960, November 15, 1960, September 28, 1961 and October 23, 1962, the transport range Λ does not depend on R while $\Lambda = 1.4\text{x}10^{12}\,R^{0.7}$ cm for February 23, 1956 and May 4, 1960 flares and $\Lambda \sim R^{0.5}$ for the November 10, 1961 flare. It is interesting to mention that $\beta = 1.0$ and Λ = const for the first four flares while $\beta = 0.5$ in the presence of dependence $\Lambda(R)$, i.e., the parameters α and β, characterizing impulse and space distribution of Λ, are probably related to each other.

The mean free path for diffusion of particles with R = 0.6 Gv in the interplanetary space increases with the decrease of solar activity: $\Lambda = 2.6\text{x}10^{13}\,\eta^{-0.6}$ cm where η is the total number of the groups of sunspots during the month.

The dependence of $\varkappa$ on r was also analyzed by Krimigis and Van Allen [90] and Bostrom et al. [91] for the February 5,

TABLE 14.5
Diffusion parameters for a series of flares of solar Cosmic rays [71]

Date of flare	Helio-coordinates	t_{max} hrs.	$\varkappa \cdot 10^{21}$, $cm^2\ sec^{-1}$	R Gv	v/c	$\Lambda \times 10^{11}$, cm	β	No. of groups of spots
Feb. 23, 1956	+74 +23	0,3	46	9,0	1,0	46	0,5	230
		0,5	28	2,8	0,95	29	0,5	
		0,6	23	2,1	0,91	25	0,5	
		0,34	41	3,5	0,95	43	0,5	
		0,46	30	4,1	0,98	31	0,5	
		0,26	53	5,9	1	53	0,5	
		0,20	69	6,0	1	69	0,5	
		0,15	92	12	1	92	0,5	
		0,14	99	14	1	97	0,5	
August 22, 1958	+18 +0,8	1,8	7,7	0,6	0,55	14	0,5	400
April 1, 1960	+11 +13	5,4	3,9	0,6	0,55	7.1	1	220
May 4, 1960	+90 +11	2,5	5,5	0,6	0,55	10	0,5	230
Sept. 3, 1960	−90 +17	5,8	3,6	2,1	0,91	4,0	1	280
		9,2	2,3	0,6	0,55	4,2	1	
		12,5	1,7	0,55	0,50	3,4	1	
Nov. 15, 1960	−60 +20	3,0	6,9	2.1	0,91	7,6	1	200
		5,4	3,9	0,6	0,55	7,1	1	
Nov. 20, 1960	+110 +20	2,8	5,0	1,5	0,85	5,9	0,5	200
July 18, 1961	+59 −0,8	2,7	7,7	2,1	0,91	8,5	1	150
		5,4	3,9	0,6	0,55	7,1	1	
July 20, 1961	+90 −0,5	1,9	7,3	0,6	0,55	13	0,5	150
Sept. 28, 1961	−29 +13	2,2	9,5	1,0	0,73	13	1	120
		2,7	7,7	0,7	0,60	12,8	1	
		3,1	6,7	0,5	0,49	13,7	1	
		3,6	5,8	0.4	0,40	14,5	1	
Nov. 10, 1961	+90 +19	0,8	17	0.8	0,63	27	0.5	90
		2,0	6,9	0,4	0,40	17,2	0,5	
		6,0	2,3	0,2	0,17	13,5	0,5	
		1,0	14	0,6	0,55	25	0,5	
Oct. 23, 1962	+70 +0,3	1,9	11	0,7	0,61	18	1	80
		2,1	9,9	0,5	0,48	21	1	
		2,5	8,3	0,4	0,38	22	1	
Feb. 5, 1965	+24 +8	4,1	3,4	0,2	0,2	17	0,5	40
July 7, 1966	+45 +34	2,8	7,4	0,6	0,55	13,4	1	120
Jan. 28, 1967		3,9	6,7	2,0	0,90	7,4	1	230
		3,9	5,3	1,0	0,73	7,3	1	

1965 flare on the basis of satellite data. In this case, the value $\beta = 2/3$ was found in [90] for protons with $\mathcal{E}_p \gtrsim 55$ Mev. On the basis of the data of stratospheric measurements, the authors [III. 107] found the value β=1.1 for the July 7, 1966 flare but on considering the experimental errors, the data [III. 107] can generally be described by β=1.0.

A flare of solar cosmic rays of small amplitude was recorded on January 28, 1967 by the world network of neutron monitors and supermonitors. The maximum increase was not more than 40% (Vostok station in Antarctica, height above sea level=3830m). The effect was observed at Mirny (Antarctica), Murmansk, Moscow and at many other stations of the world network. Time variation of this flare at Moscow and Deep River is shown in Fig. 14.18. The maximum increase at these stations (supermonitors) was 16% and 6% respectively. Asymptotic straight lines corresponding to fall of intensity according to laws $t^{-3/2}$, t^{-2} and t^{-3} are also shown here. It is seen that the law $t^{-3/2}$ (elementary diffusion model) is not suitable for explaining the time variation after maximum. The phase of decrease for this flare is apparently described by the law $\sim t^{-2}$ or $\sim t^{-3}$.

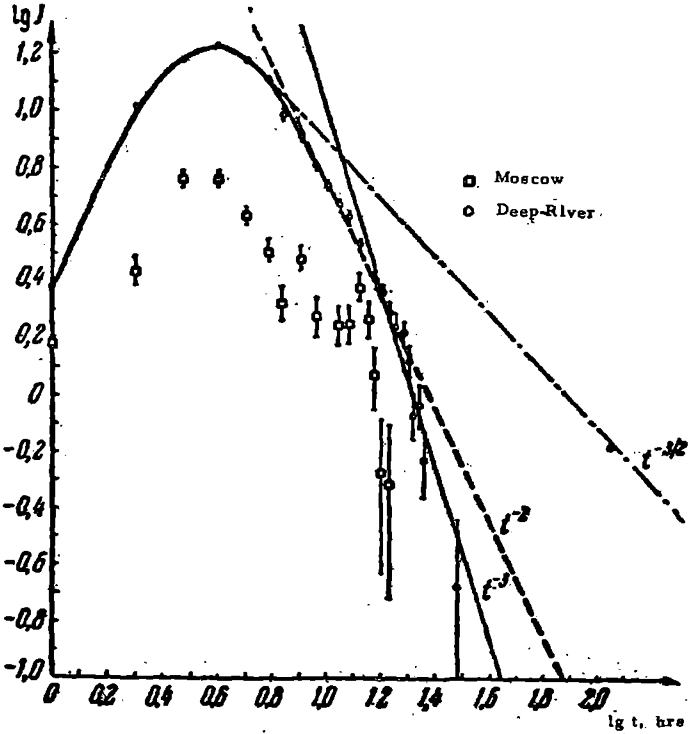

Fig. 14.18. Time variation of intensity of particles from the January 28, 1967 for Moscow and Deep River stations.

Fig. 14.19 illustrates the dependence of $\ln It^{3(2-\beta)}$ on t^{-1} for Deep River at $\beta = 0$ and $\beta = 1$. According to Fig. 14.19, the initial stage of the flare can be approximately described by a constant diffusion coefficient ($\beta=0$) but immediately after the max imum, such a description becomes unsuitable. If the data for Deep River are plotted as $\ln It^3$ on t^{-1}, we get satisfactory conformity to the value $\beta=1.0$ [52]. Thus, it can be assumed that all the existing data on the dependence of $\mathcal{X}$ or r satisfy the values of β in the range 0.5-1 or more accurately, $0 \leq \beta \leq 1.0$.

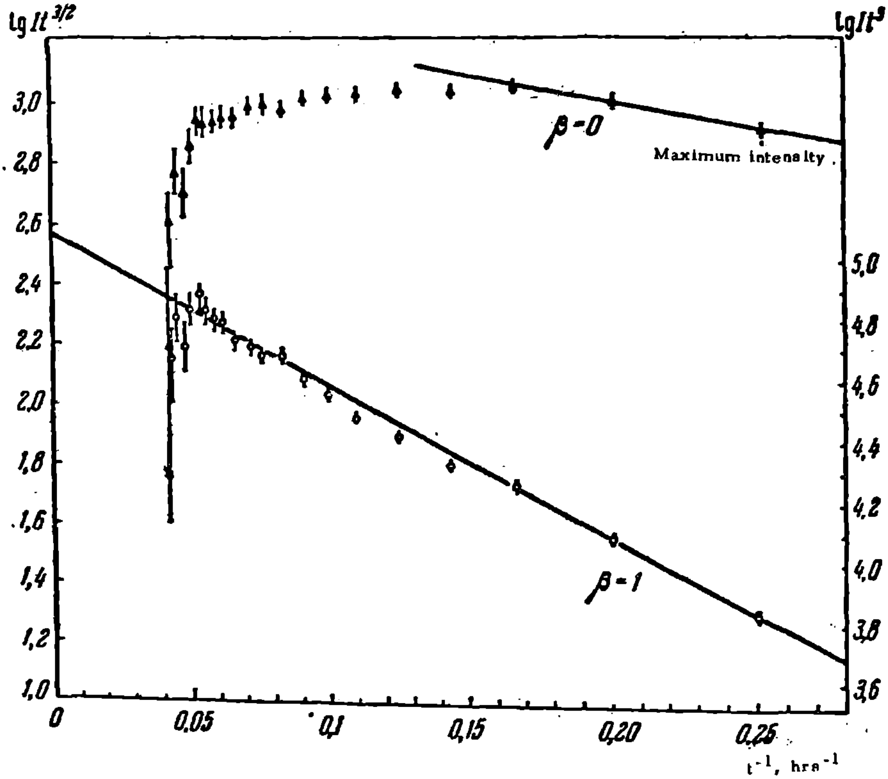

Fig. 14.19. Data on the January 28, 1967 flare for Deep River station at different values of β.

Interpretation of the dependence $\mathcal{X}(r)$. The dependence of $\mathcal{X}$ on r has a direct relation with the structure of the interplanetary space and modulation mechanisms of galactic cosmic rays. Parker [I. 61] introduced the concept of "diffusion resistance" of interplanetary medium which a galactic particle must experience during its motion from infinity in the solar system to a given system (for example, up to $r = r_{\text{♁}}$). Physically, it means that the number q of transport range Λ of a galactic particles between infinity and $r_{\text{♁}}$ must be finite if the particle reaches up to $r = r_{\text{♁}}$ and infinite if the particle does not attain $r = r_{\text{♁}}$.

The value of q is determined from the integral

$$q \sim \int_{r}^{r_2} \frac{dr}{\Lambda}. \tag{14.49}$$

If the model of open interplanetary space is adopted (i.e., with the gradual decrease of the density of scattering centers), the effective value of β in the three-dimensional case must be more than one. Actually, from (14.44) it follows that $r_2 \rightarrow \infty$ and $\Lambda \sim r^{\beta}$ where $\beta \lesssim 1$, we get $q \rightarrow \infty$ whereas at $\beta > 1$, q has a finite value. It means that only at $\beta > 1$, galactic cosmic rays can penetrate into the solar system. Since the data on all the flares investigated give the value $\beta \lesssim 1$, it should be assumed in the case of the open model of the interplanetary space that galactic particles of energy, for example, $\mathcal{E}_k \lesssim 500$ Mev (if the results of the September 28, 1961 flare are taken into account) do enter the Earth's orbit.

Recently, Hofmann [92] while studying the effects of modulation of primary particles with R = 0.1-10 Gv during 1963-65 got the value $\beta = 1 - 1.08$. In our opinion, this result related to the open model is wrong since in [92]: 1) the effect of delay is not considered; 2) $\Lambda(r)$ is not under the sign of differentiation with respect to r; 3) steady problem is solved while the obtained solution depends on t; 4) stratospheric data of Ormes and Webber [93] are used, which are not free from the contribution of secondary particles.

If it is assumed that the mean free path is constant or decreases on increasing r, i.e., $\beta \leq 0$ or $\Lambda \sim \exp(-r/r_{\delta})$, then at $r_2 \rightarrow \infty$, we again get $q \rightarrow \infty$. On the other hand, if Λ increases with distance, i.e., $\Lambda \sim \exp(r/r_{\delta})$, then q = const, i.e., finite. Thus, out of the considered cases of the dependence $\Lambda(r)$ only two cases satisfy the open model: $\Lambda \sim r^{\beta}$ $(\beta < 1)$ and $\Lambda \sim \exp(r/r_{\delta})$.

Experimental data, point out the presence of galactic cosmic rays of energies much less than 500 Mev near the Earth (it is appropriate to mention that the maximum of their spectrum lies in the region ~400 Mev/nucleon). Moreover, pressure of solar wind — carrier of the interplanetary fields — must be balanced by the pressure of the interestellar gas at a particular distance from the Sun [I. 61]. It should also be mentioned that the interpretation of time variation of solar particles at large values of t on the basis of the dependence $\varkappa(r)$ is not the only possible interpretation. For example, if there exists an effective magnetic boundary of diffusion region of radius r_0 (see Section 14.3), concentration at the Earth's orbit decreases not according to the power law but according to the exponential law and the diffusion coefficient depends only on R. In this case, as mentioned in Section 14.1, diffusion rate $v = 3\varkappa/r_0$ = const for particles of a given energy. If, on the other hand, $\varkappa$ increases with distance as $\sim r^{1.0}$ and there is no boundary, the condition v_d = const should, even then, be satisfied.

It is obvious that the diffusion rate cannot be more than the velocity of propagation of particles in the absence of magnetic fields and matter (in vacuum), i.e., $v_d \leq v$. As can be seen from (14.11), the equality $v_d = v$ corresponds to the case when $\Lambda = r$, i.e., the transport range is equal to the distance, covered along the radius, from the Sun. On the other hand, the distance covered $r = vt$ and the volume occupied by particles in the three-dimensional case will be $V \sim r^3 = (vt)^3$. Concentration of particles, averaged for this volume, will change according to the law $n \sim V^{-1} \sim r^{-3} \sim t^{-3}$. Comparing this result with (14.44), it is not difficult to notice that the value $\beta = 1$ satisfie
the decrease in concentration according to the law $\sim t^{-3}$.
a limitation is obviously put, by the model of diffusion pro
in the three-dimensional isotropic space, on the rate of i
crease of diffusion coefficient on increasing the distan
the Sun, i.e., the value of β must satisfy the condi
since at $\beta \geqslant 1$, the model con dered here i
is comparable to the distance

Thus, the above-ment
smic rays with $\mathcal{E}_k \lesssim 100$ M
undary for solar wind, limitatio
$\varkappa \sim r^{\beta}$ by the value $\beta \lesssim 1$, the possible existence of an effective boundary of diffusion region) are apparently in favor of a closed model of the interplanetary space.

This conclusion, applicable only within the framework of the diffusion model under reference, can have great significance for the theory of modulation mechanisms of cosmic rays, in particular, for the theory of 11-year variations. Here, it should be kept in view that solar cosmic rays provide information only on the space of radius $r_x \lesssim 10$ a.u. (see Section 14.1). Beyond this distance, the electromagnetic situation may be absolutely different from that in the internal part of the solar system as the interstellar magnetic field near the solar system is not a homogeneous field of galactic sleeve as was considered earlier but has a very complicated structure (see Section 13.1).

Dependence $\varkappa(r)$ and properties of the source. As is seen from (14.44), solution of the generalized diffusion equation must satisfy the condition $\beta < 2$ and the value of β must lie within the limits $0 \leq \beta \leq 2$ on considering the problem of the emission of particles from a source not situated at origin of coordinates [94]. If $\beta \to 2$ on the left, concentration of particles on the Earth's orbit $n \to 0$. It means that the particles from a source situated at the center ($r = 0$) do not reach the Earth. Actually, at $\beta = 2$, the integral (14.49) within the limits from $r_1 = 0$ to $r_2 = r_{\delta}$ is a diverging integral, i.e., the "diffusion resistance" between origin of coordinates and the Earth's orbit is infinite. It was assumed in works [26, 72] that the particles were emitted at the point $r = 0$ and therefore, the condition $\beta < 2$ has a purely formal sense since the particles in reality are not generated at the center of symmetry.

It should be mentioned that not β but the parameter $s = (\sigma + 1)/(2 - \beta)$ can be determined experimentally. Therefore, concentration can decrease according to the law $\sim t^{-3/2}$ not only in an isotropic, spherically symmetrical medium. The equality $s = 3/2$ is also valid at $\sigma = 1$ and $\beta = 2/3$ (one-dimensional diffusion), $\beta = 0$ and $\beta = 4/3$ (two-dimensional diffusion), $\sigma = 3$ and $\beta = -2/3$ (diffusion in a pipe-shaped medium), etc. The last case contradicts the assumption that $\varkappa$ increases on increasing the distance from the Sun.

It should be mentioned that this model is comparatively unsuitable for explaining the data obtained during the initial stage of a flare. This is apparently related to the initial anisotropy and prolonged emission of particles from the acceleration region.

Summing up the results of this Section, let us once again point out that the values $\beta \lesssim 1$ at $\mathcal{E}_k \lesssim 500$ Mev must point out the absence of particles of such energy in the composition of galactic cosmic rays near the Earth. This assumption however contradicts the observations (see Fig. 11.8). Moreover, it is absolutely natural to expect that the value of β increases at higher energies; possibly, β changes with the solar acitivity in accordance with different turbulent states of the interplanetary medium.

Thus, even if r_2 in (14.49) is considered to be infinite, in spite of a number of arguments in the favor of the closed model of the interplanetary space, it is not clear if there exists any physical contradiction. Nevertheless, it can be expected that the obtained empirical values of β can throw some light on the general problem of modulation of the spectrum of galactic cosmic rays in the interplanetary space. Study of the change $\beta(\mathcal{E})$ during solar cycle is of special interest. Some views on the dependence of diffusion coefficient on the epoch of solar activity are mentioned in Section 14. 5.

As mentioned by L.I. Miroshnichenko [95], while studying the dependence of $\varkappa$ on r, the correct consideration of low-energy background is very important (see Section 11) whose contribution to the observed intensity is not constant with time and can be significant when the flux of particles from the flare being studied becomes comparable to the background. In particular, as seen from (14. 44), the decrease in the experimental values of I due to wrong consideration of background leads to an increase in the value of β.

Measurements on the intensity of cosmic rays simultaneously at different points of the interplanetary space are very important for formulating a theory of propagation of cosmic rays in the solar system and for studying the properties of the interplanetary medium. Such measurements were, for the first time, made by S.N. Vernov et al. [96] on the satellites "Zond-3", "Venera-2" and "Venera-3". It facilitated determination of gradient concentration of protons having $\mathcal{E} = 1$-5 Mev at distances from 130 to 190 million km from the Sun. The observations led to the unexpected conclusion regarding the existence of a large gradient (the intensity increased by about 5 times on increasing the distance from the Sun to 190 million km). One of the possible qualitative expalanation to the observed distribution of protons, mentioned in [96], is the assumption that a large number of protons can be thrown beyond the Earth's orbit along comparatively narrow channels during solar flares (even during small flares). Afterwards, the protons diffuse in all the directions including the direction towards the Sun.

Assuming the result [96] experimentally reliable and considering that the motion of protons observed in [96] has the nature of diffusion, A. Z Dolginov and I.N. Toptygin [97] made an attempt to determine the dependence of diffusion coefficient on the distance without specifying the location of the source of particles. (It is only important that the source existed outside the region being studied). The authors solve the equation of diffusion of particles for the case when the magnetic irregularities move in space with a regular velocity u. According to [97], the diffusion coefficient as a function of distance depends on the index γ of the spectrum of protons and on the value of $\varkappa_z$. Since correct values of r and $\varkappa_z$ are not known, it is not possible to determine the exact dependence $\varkappa(r)$. However, as shown in [97], there is a significant, by 5-10 times, decrease of diffusion coefficient on increasing r in the region at all reasonable values of γ and $\varkappa_z$. This result apparently points out the fact that on increasing the distance from the Sun and particularly between the orbits of the Earth and the Mars, regularity of the field is distrubed to even greater extent, its lines of force get entangled and irregularities of lesser dimensions appear. In the case of appearance of irregularities of the field of dimensions $l \lesssim \rho$, scattering of protons is sharply intensified and the mean free path decreases. If the arbitrary field H_1 is much less than the regular field, then as it follows from the theory [35], it increases according to the law $(H_1^2) \sim \varkappa^{-1}$.

Diffusion coefficient, not depending on an arbitrary distance $\varkappa_z$, can be more directly determind with the help of the formula for the density J_i of the beam of particles [97]. But, in this case, it is necessary to measure the components of current J_i along with the concentration gradient and spectrum.

14.7. Spectrum of solar particles in the source. The relations (14.44) and (14.45) in some cases make it possible to determine the spectrum of solar particles in the source. At $\beta=0$ and $\sigma = 2$, the relation (14.45) becomes

$$\ln\left[I(r_\delta, t)t^{3/2}\right] = \ln\left[\frac{Nv}{4\pi(2\sqrt{\pi\varkappa})^3}\right] - \frac{r_\delta^2}{4\varkappa}\frac{1}{t}. \qquad (14.50)$$

On the basis of data [I.23] on the Septmber 28, 1961 flare, the authors [64] plotted the dependence of ln $It^{3/2}$ on t^{-1} at different values of the energy of solar protons (Fig. 14.20). The dotted and full lines on Fig. 14.20 correspond to two methods of processing of the data with the help of (14.50); in the first case, t was counted from the beginning of X-ray flare while in the second case, from the time when X-ray flare was at its maximum (difference in these times is of the order of 10 min). It is seen that the propagation of particles with $\mathcal{E}_k < 100$ Mev is described by the equation of isotropic diffusion for the whole time range for which the experimental data is available. The beam of particles with $\mathcal{E}_k \gtrsim 100$ Mev became isotropic about 9×10^3 seconds after the maximum of X-ray flare; later on, the propagation was due to diffusion, for about 1.7×10^4 seconds, after which the rate of decrease of intensity deviated significantly from the law $\sim t^{-3/2}$ (three short straight lines in the right-hand side of Fig. 14.20). Times of maximum intensities, shown in Fig. 14.20 by arrows, occurred during the period of isotropy. Particles with $\mathcal{E}_k \sim 3$ Mev

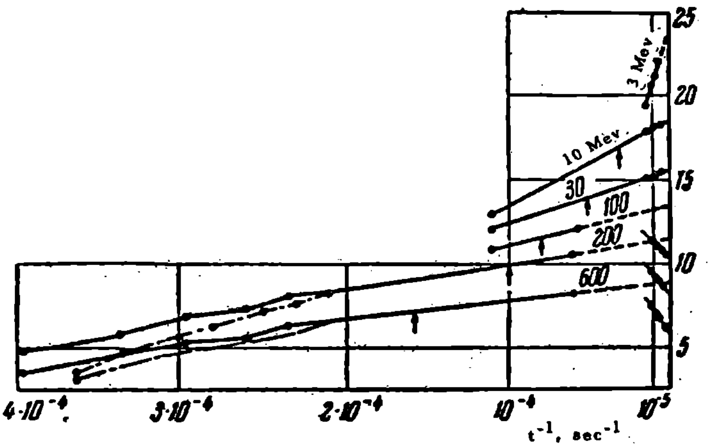

Fig. 14.20. Dependence of lnIt$^{3/2}$ on t^{-1} for the intensity of solar particles from September 28, 1961 flare [64] at various values of the energy of particles.

were an exception for which maximum was not attained during observations (their intensity continued increasing right up to the commencement of geomagnetic storm).

For the case of 200 and 600 Mev particles, it is seen from Fig. 14.20 that selection of the time of beginning of emission is important for the first, anisotropic phase of propagation of solar particles and stops playing a significant role after the appearance of isotropy. It is also seen that better conformity of experiment to the theory of isotropic diffusion is observed in that case when the time of maximum of X-ray flare, attained 15 minutes after the beginning of September 28, 1961 chromospheric flare, is taken as the beginning of emission of particles. This result is in agreement with the data of Hofmann and Winckler [III. 88] for the July 18, 1961 flare.

Extending the straight lines of Fig. 14.20 till they intersect the ordinate axis at $1/t = 0$, it is possible to calculate from (14.50) the number of emitted particles of different energies. The differential spectrum for this flare, obtained in this manner, has the form $D(\mathcal{E}_k) = 5.6 \times 10^{34} \ \mathcal{E}_k^{-2}$ particles/Mev. During diffusion, the spectrum must diffuse owing to the dependence $\varkappa(\mathcal{E})$. In order to compare with measured data on September 28, 1961 flare, differential spectrum on the Earth 36 minutes (2.16×10^3 sec) after the maximum of X-ray flare shows that the maximum of the spectrum was in the region $\mathcal{E}_k \sim 100$ Mev which approximately corresponds to measurements [I. 23] at 2320 UT.

Emission spectrum can be obtained from (14.7) or (14.50) by a simple calculation by having the data on differential intensity $I(r_{♁}, t)$ and values of $\varkappa$ at various energies. However, the above-mentioned method is more clear since Fig. 14.20 not only demonstrates the applicability of the theory of isotropic diffusion to propagation of solar cosmic rays but also shows the limits of this applicability with time. In many cases, time variation of the intensity of solar cosmic rays cannot be correctly described by the elementary diffusion model. However, in most of the cases, such a description is valid at least within a limited interval of time during which the beam of solar particles is isotropic. Thus, if diffusion takes place even during a limited interval of time and if the differential spectrum of solar particles is measured, there appears, in principle, the possibility of getting the very important characteristics of acceleration mechanism on the Sun, namely, spectrum of accelerated particles at the time of their emission.

Assuming that the obtained emission spectrum extends right up to 1 Mev, it is possible to calculate the total number of emitted particles of energy more than the given one. Although, the total number of generated particles with $\mathcal{E}_k$ = 1 - 1000 Mev is very large (5.6×10^{34}), the energy contained in them (6.2×10^{29} erg) is not more than the kinetic, magnetic or optical energy of a class 3 or 3^+ flare.

Bryant et al. [I. 55] obtained emission spectra of the form $\sim \mathcal{E}_k^{-\gamma}$ for the flares of September 28, 1961 ($\gamma = 1.7$), November 10, 1961 ($\gamma = 1.5$ for $\mathcal{E}_k = 1.4$-22 Mev and $\gamma = 3.5$ for the range $\mathcal{E}_k$ = 55-500 Mev) and October 23, 1962 ($\gamma = 2.3$) (Fig. 14.21).

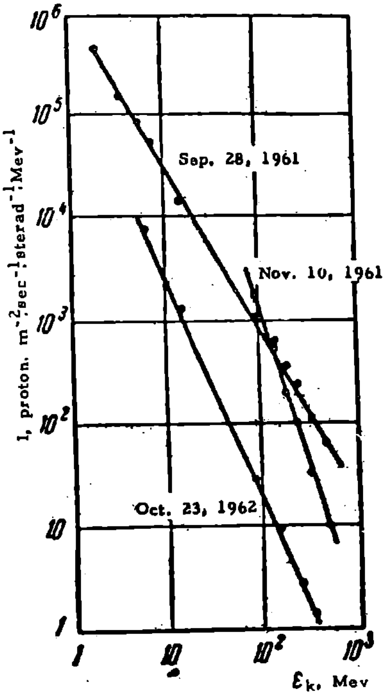

Fig. 14.21. Generation spectra for the flares of September 28, 1961, November 10, 1961 and October 23, 1962 [I.55].

Emission spectrum for the September 28, 1961 flare [64; I. 55] does not contradict the results of the work of A.A. Korchak

[99] in which the spectrum of nonrelativistic electrons was obtained from the analysis of X-ray and radio emission for the same flare. Difference in the values of the index γ can be explained by the difference of energy losses of protons and electrons in the solar atmosphere.

An interesting analysis of the data of September 28, 1961 flare was done by Krimigis [28] on the basis of the generalized diffusion model by considering the dependence of diffusion model on the energy of particles and distance from the Sun. As is seen from (14.44) and (14.45), knowing the values of $\varkappa_{\pm}$ and β, it is possible to calculate the total number of particles emitted at the time t=0 and further, using the data for various energies, it is possible to plot the spectrum of particles at the time of emission t = 0. Expressing the obtained results in four ways, namely power function of $\mathcal{E}_k$, exponential function of $\mathcal{E}_k$, power function of R and exponential function of R, Krimigis arrived at the conclusion that each of these functions can be used for des- In the opinion of Krimigis, best approximation is obtained for the exponential rigidity spectrum (Fig. 14.22). The vertical errors obtained approximately are maximum and the actual errors are probably lesser. Differential spectra for the three methods (excepting the exponential function of energy) have the form:

$$dN/d\varepsilon_{к} = 2{,}23 \cdot 10^{32}\, \varepsilon_{к}^{-(2{,}41 \pm 0{,}3)} \text{ particle/Mev}, \qquad (14.51)$$

$$dN/dR = 8{,}87 \cdot 10^{36}\, R^{-(3{,}7 \pm 0{,}3)} \text{ particle/Mv}, \qquad (14.52)$$

$$dN/dR = 1{,}53 \cdot 10^{28}\, e^{-R/(173 \pm 30)} \text{ particle/Mv}. \qquad (14.53)$$

It is obvious that the spectrum in the form (14.51) does not contradict the results [64; I. 55]. Calculation of the number of particles of energy $\mathcal{E}_k > 23$ Mev (i.e., of rigidity $R > 209$ Mv) is the appropriate verification of the relations (14.51)-(14.53). From (14.53), we get $N(R > 209 \text{ Mv}) = 0.79 \times 10^{30}$ particles. This value is well in agreement with the value of 1×10^{30}, calculated directly from (14.44) with the help of graphs given in Fig. 14.10, a. The power function of energy (14.51) or rigidity (14.52) gives the values 1.88×10^{30} and 1.82×10^{30} particles respectively.

Simple calculations show that a very small fraction of the total energy of flare is contained in such an amount of particles.

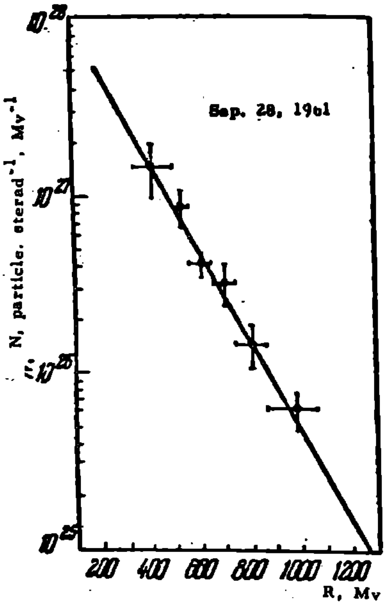

Fig. 14.22. Exponential rigidity spectrum for the September 28, 1961 flare at the time of emission.

If the dimension of the falre is taken to be $\sim 10^4$ km with magnetic fields H = 1000 gauss, the total energy, contained in magnetic field, will be of the order of 10^{31} erg. On the other hand, the total energy of 1.26×10^{31} particles having $\mathcal{E}_k \approx 23$ Mev is equal to $\sim 4.6 \times 10^{26}$ erg which is less than 10^{-4} of the energy contained in the flare region.

It is interesting to study the time evolution of spectrum. It can be done on the basis of the relation (14.46) by using the constants given in Table 14.4. According to calculations [28], spectrum "bends downward" at low values of t and gradually softens with time (Fig. 14.23). These results agree with the observations of internal coordination of the model which takes into account the dependence $\varkappa(\mathcal{E}, r)$.

The experimental indications of the fact that spectrum becomes more plane at low values of energy [I.2, Section 50] were taken into account in L.I. Miroshnichenko's work [44] while calculating the rigidity spectra of solar particles at $\beta = 0, \sigma = 2$. In order to specify, it was assumed that the spectrum of particles with $\mathcal{E}_k \sim 10$ Mev is plane at the time of emission, i.e., $\gamma = 0$ while $\gamma = 2$ ($\mathcal{E}_k$ = 100-500 Mev) and $\gamma = 3$ ($\mathcal{E}_k \gtrsim 600$ Mev) at higher energies.

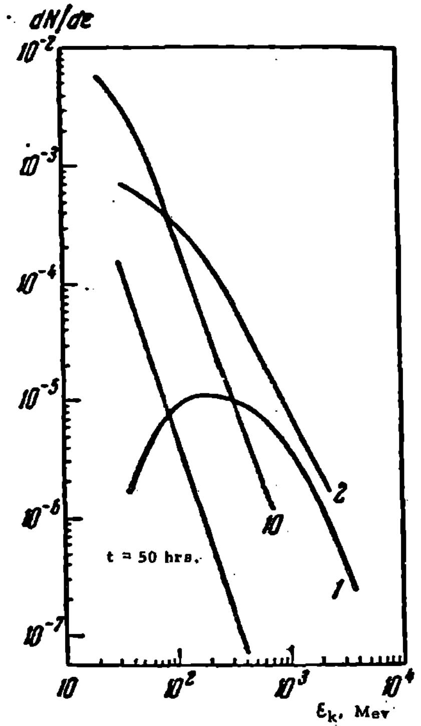

Fig. 14.23. Spectrum of solar protons expected at different moments of time at the Earth's orbit.

Differential rigidity spectra are shown in Fig. 14.24 for
$t_1 = 10^4$ sec after the commencement of emission and $t_2 = 10^5$
It is, first of all, seen that there is a tendency to spectral
ng with time and that this tendency is most clearly expres-
he region of extremely low and very large values of R.
nple, at $R = 10^4$ Mv. concentration of particles at t_1 is
that at t_2 by about three orders. Moreover, in both the
ctrum has a maximum whose position displaces in the
low values of R on increasing t. The maximum at
ry sharp and is situated near the value R = 250 Mv. At
2, the maximum is more diffused and lies in the range of 70-100 Mv.

It is interesting to mention that on considering the dependence $\varkappa(R)$, diffusion does not change with time the power nature of pectrum starting from $R \approx 250$ Mv ($\varepsilon_k \approx 30$ Mev). Inclination of spectra at $R \geqslant 1730$ Mv ($\varepsilon_k \gtrsim 1$ Gev) corresponds to the values $\gamma = 3.5$ at t_1 and $\gamma = 6$ at t_2. The spectra become more slant-

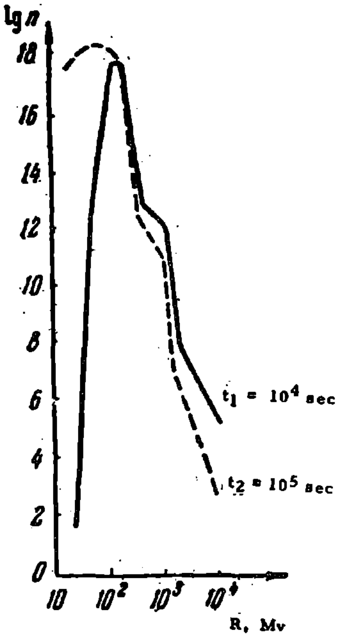

Fig. 14.24. Rigidity spectra at the Earth's orbit expected at various moments of time in the case of power spectrum of emission with variable γ.

ing in the region of lower values of R. In general, this aspect of spectra does not contradict the experimental data. However, the measured spectrum has a smoother form than the calculated one. Therefore, it can be assumed that the emission spectrum has the power form and the index gradually decreases to $\gamma = 0$ in the region of very low rigidities.

For understanding the processes giving rise to the spectrum of solar cosmic rays at the source, it is important to determine emission spectra for different energy ranges. The result obtained by L.I. Miroshnichenko [88] for the flares of February 23, 1956, May 4, 1960 and January 28, 1967 are described below.

Fig. 14.17 shows the data on February 23, 1956 flare for 6 mountainous neutron monitors, processed with the help of (14.45) at $\beta = 0.5$. Points of intersection of straight lines with the ordinate at $t^{-1}=0$ give, with the accuracy of the constant factor, values of the intensity of particles $I(>R)$ of rigidity $R > R_{min}$ for the given observation post. Integral spectrum of solar partiicles from February 23, 1956 flare at the time of emission was obtained in this way. This spectrum is shown in Fig. 14.25 in arbitrary units in semilogarithmic (curve 1) and logarithmic scales (curve 2). It is seen that $I_0(>R) = I_0R^{-4.5}$ while the accuracy of determination of index is apparently not less than ± 0.5. From this, we get the differential emission spectrum $D_0(R) = D_0R^{-5.5\pm0.5}$.

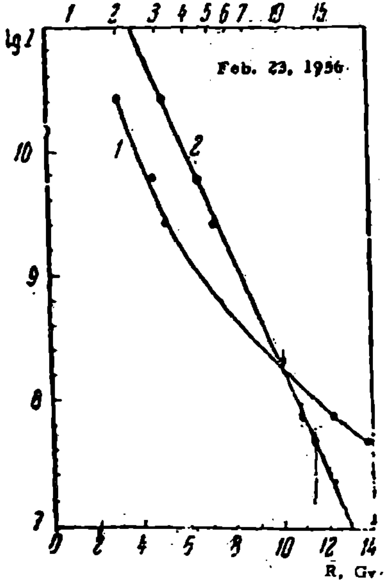

Fig. 14.25. Integral emission spectrum for February 23, 1956 flare in semilogarithmic (1) and logarithmic (2) scales.

Let us compare the last result with the spectrum measured on the Earth. According to [I.36], differential spectrum measured in the same rigidity range has the form $\sim R^{-7.0\pm0.5}$. The spectrum apparently deforms in the process of diffusion of particles in the interplanetary space due to the dependence of $\varkappa_{\pm}$ on R. It can be noticed from the difference in the inclination of straight lines in Fig. 14.17 for the stations Climax and Huancayo that $\varkappa_{\pm}$ increases by about 4 times on increasing R from 3.08 to 13.7 Gv. It follows from this that in the relativistic energy range $\varkappa_{\pm} \sim \Lambda \sim R^{1.0}$. On considering this result (as well as the result [71] where $\Lambda \sim R^{0.7-0.8}$, it can be seen from (14.45) that the measured differential spectrum actually corresponds to emission spectrum (within the limits of the above-mentioned accuracy).

Pfotzer [I. 45] determined distribution of the intensity of particles, directly coming from the Sun, on the Earth's surface by substracting the data of background zone from the results of observations in shock zones. The spectrum of direct beam, obtained in this way, had the form $\sim R^{-3.4}$ in the range R = 2.5-6 Gv which is in agreement with the results of calculated spectrum [I. 1] for the time 0400 UT on February 23, 1956. In accordance with the theory of diffusion, spectrum of direct beam must be more rigid than the emission spectrum. The above-obtained results confirm this conclusion. It should also be mentioned that consideration of the result [I. 45] as emission spectrum leads to unjustified increase in the value of a in the relation $\Lambda \sim R^{a}$. According to [74], values of a lie in the range 1.8-2.4 which contradicts the above-obtained value $a \lesssim 1$.

The May 4, 1960 flare was distinguished by the presence of shock zones which were displaced as compared to the locations expected from calculations [I. 7]. Moreover, the maximum increase in the intensity of solar particles was recorded at stations situated on the American continent and Australia while the European stations were found to be in the background zone. Comparatively low amplitude of outburst ($\lesssim 35\%$ in the neutron component) and small duration (not more that 2 hours at most of the stations) are the characteristic features of this flare. Therefore, data of only those stations where measurements were conducted for short periods (2-5 minutes) were found to be suitable for determining emission spectrum while the data obtained after the maximum outburst were used for stations in the shock zones.

Data on neutron component for the mountainous stations of Sulfur (R_{min} = 1.10 Gv), Washington (1.34 Gv) and Tsugspittse (4.52 Gv), processed on the basis of (14.45) at $\beta = 0.5$, is shown in Fig. 14.26. Times of maximum outbursts are shown by arrows. Taking into account large measurement errors at the end of the event, from Fig. 14.26, we get the value $\beta' = 0.5$ which satisfactorily agrees with the observational data. The integral emission spectrum, which has the form $I_{\odot}(>R) = I_0 R^{-2.5 \pm 0.5}$ within the limits of 1.1-4.52 Gv, is also shown in the same Fig. from where it follows that $D_{\odot} \sim R^{-3.5 \pm 0.5}$. If $\varkappa_{\oplus} \sim R^{1.0}$, then, in accordance with the observations [I. 35], the spectrum on the Earth's surface at $t \gg t_{max}$ will be $D_{\oplus} \sim R^{-5 \pm 0.5}$.

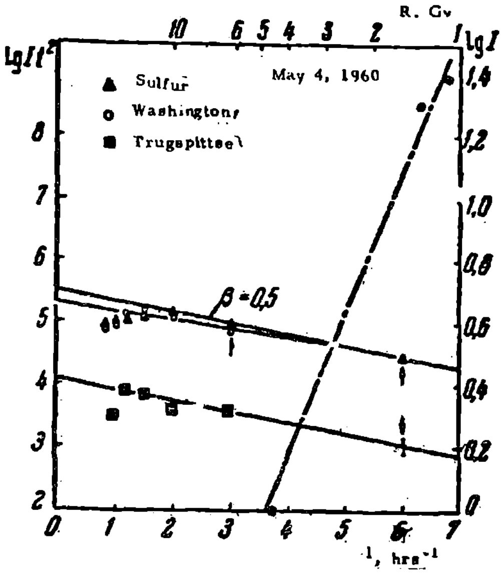

Fig. 14.26. Data on three mountainous stations for the May 4, 1960 flare at $\beta = 0.5$ and the integral emission spectrum (on the right).

The January 28, 1967 flare was also characterized by low amplitude ($\lesssim 40\%$ in the neutron component) but it lasted for about one day (at stations having low cut-off rigidity). According to preliminary data, no chromospheric flares were recorded during the period January 27-29, 1967, solar activity was low and the geomagnetic field was quiet.*

We have already analyzed, in Section 14.6, time variation of solar particles for this flare on the basis of data of neutron supermonitors installed at Moscow and Deep River. Fig. 14.27 shows preliminary data on the latitude effect of the flare (curve 1) in the range R = 0.1-5.0 Gv as well as emission spectrum $D_\odot \sim R^{-3.5\pm0.3}$ (2) and the spectrum $D_{\oplus} \sim R^{-5.5\pm0.3}$ at the Earth's orbit (3) (at the time of maximum outburst). The emission spectrum was obtained from the data of Moscow and Deep River stations on the basis of (14.45) at $\beta = 1$ while the spectrum on the Earth was determined from the data of Deep River, Durkhem, Moscow and Dallas stations on the basis of the procedure worked out in [I. 36] and described in Section 2. Both the spectra belong to the rigidity range R = 1-5 Gv. By comparing these spectra with the help of (14.44) at $\beta = 1$, it can be concluded that $\varkappa_\perp \sim R^{0.5-1}$. If this dependence is also retained at $R \lesssim 1$ Gv (i.e., if the measured spectrum does not change its inclination at very low values of R), then at $\varkappa \sim R$, we get $\Lambda \approx$ const for nonrelativistic particles.[**]

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* *According to the data obtained at the Crimean Astrophysical Observatory ("Solar data", Izd-vo "Nauka", 1967, No. 1), a class 1 flare was recorded at 0728-0858 UT on January 28, 1967 in the active region with coordinates 23°S, 19°E. At the same time, a radio outburst on a frequency of 3100 MHz and an increase in the level of radio emission on meter band was observed. Many subflares (not less than 4) were also recorded in the same active region.*

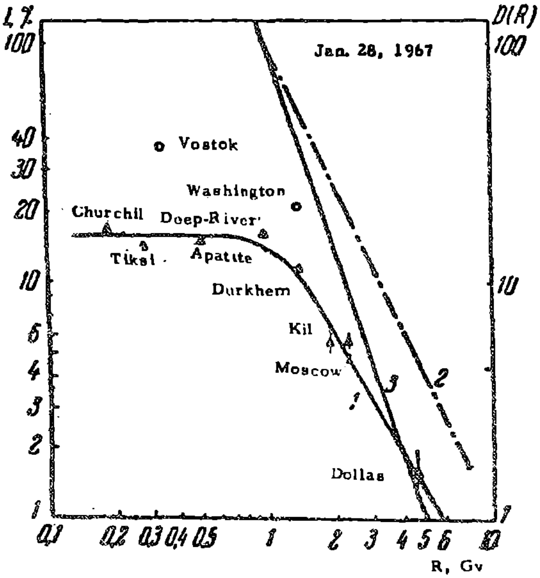

Fig. 14.27. Latitude effect (1), emission spectrum (2) and spectrum on the Earth's orbit (3) for the January 28, 1967 flare.

Emission spectra, obtained by us and by other research workers, are given in Table 14.6 for many flares. Data on spectra of November 10, 1961 and October 23, 1962 flares are taken from [I. 55]. It is seen that within the limits of errors, emission

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[**] *N. P. Chirkov et al. [127] studied the January 28, 1967 flare on the basis of the data of 15 stations (neutron component). Time variation of solar particles is described by diffusion model at* $\beta = 1.0-1.2$; $\Lambda = 6.5\mathrm{x}10^{11}$ *cm and* $\varkappa = 6.5\mathrm{x}10^{21}$ *cm*^{2}*/sec (for relativistic protons). These values of* Λ *and* $\varkappa$ *are much less than those obtained for other flares in the same rigidity range. It is probably caused by the fact that the active region, responsible for the flare, was situated in the south-eastern quadrant of the visible disk of the Sun and therefore, solar protons moved at a large angle with the lines of force of the interplanetary field.*

TABLE 14.6

Emission spectra for some flares

Date flare	Energy range, Gv	Rigidity range, Gv	Emission spectrum, γ	Spectrum at the Earth's orbit, γ
Feb. 23 195	3 - 14	3 - 14	5.5 ± 0.5	7 ± 0.5
May 4, 1960	0.50 - 4.0	1.1 - 4.52	3.5 ± 0.5	4.5 ± 0.5
Sept. 28, 1961	0.001 - 0.5	0.05 - 1.1	3.7 ± 0.3	5.2 ± 0.3
Nov. 10, 1961	0.001 - 0.022	0.05 - 0.20	3 ± 0.3	
	0.055 - 0.5	0.39 - 1.1	7 ± 0.3	
Oct. 23, 1962	0.004 - 0.33	0.086 - 0.850	4 ± 0.3	
Jan. 28, 1967	0.5 - 4.5	1 - 5	3.5 ± 0.3	5 ± 0.3

spectra for the flares of May 4, 1960, September 28, 1961, October 23, 1962, and January 28, 1967 coincide in the rigidity range $0.2 < R < 5$ Gv. Spectrum of the November 10, 1961 flare in the range $R = 0.39$-1.1 Gv is the only exception.

The tendency towards decrease in the inclination of spectrum in the region of low rigidities is obvious from Table 14.6 while following are the values of the index: $\gamma = 5.5. \pm 0.5$ in the range $R = 3$-14 Gv, $\gamma = 3.8 \pm 0.3$ (average value of four flares in the range $R = 0.2$-5 Gv) and $\gamma = 3.0 \pm 0.3$ ($R = 0.001$-0.20 Gv). The November 10, 1961 flare apparently requires additional investigation since this chromospheric flare of class 1^{+} was accompanied by the origin of unusual loop-shaped protuberances [I.55].*

It is important to mention that the difference in the values of γ for very rigid (3-14) Gv) and soft particles (< 5 Gv) goes beyond the limits of experimental errors. This fact can point out the difference of acceleration mechanisms for particles of high and low energies.

14.8. Duration of emission of solar particles. It follows from equation (14.6) that the solution of spherically symmetrical diffusion problem (14.5) for an infinite space is mainly determined by the form of F function. The density of source F or injection function is the number of particles emitted in unit time from the generation region. This function is determined by the nature of the process of acceleration of particles on the Sun and by the process of their exit through corona and supercorona. In the general case, F can depend on the energy of particles and time.

At present, we do not have sufficiently detailed information on the nature of dependence of F on $\mathcal{E}_k$ and t. From experience, only this is known (for example for November 19, 1949 and February 23, 1956 flares) that F quickly attains maximum after the commencement of chromospheric flare and that it decreases sharply afterwards according to an exponential law (for example, for February 23, 1956 flare, $F(\varepsilon_k, t) \sim e^{-t/T_0}$ where $T_0 \approx$ 15 min). The emission function at low energies may be significantly extended with respect to time which partially gives rise to the delay of low-energy particles.

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* *Interesting ionospheric effects in polar caps were observed during November 10, 1961 flare (Banks and Sechrist [II.87] - change in the absorption of cosmic radio noises at a frequency of 30 MHz; Bates [II.88] - significant distortions of the phase and amplitude of radio signals of frequency 3-30 kHz along the path England-Alaska).*

Let us assume that F can be approximated by one of the following expressions (the source is taken to be point source):

$$F(\varepsilon_\kappa, t) = N(\varepsilon_\kappa)\delta(t), \tag{14.54}$$

$$F(\varepsilon_\kappa, t) = N\begin{cases} T^{-1}, & 0 \leqslant t < T, \\ 0, & t > T, \end{cases} \tag{14.55}$$

$$F(\varepsilon_\kappa, t) = N(\varepsilon_\kappa)e^{-t/T_0}, \tag{14.56}$$

where $N(\varepsilon_k)$ is the number of emitted particles of energy ε_k; T is the time of activity of the source and T_0 is a constant characterizing the emission rate of particles; t being counted from the commencement of emission. The case of instantaneous emission of particles (14.54) is very convenient mathematically for solving the equation (14.5) because of the properties of δ-function. This case has been analyzed in detail in literature. In the recent past, experimental data were obtained (see Section 11.2) which pointed out to the possibility of accumulation of low-energy solar particles in the interplanetary space during the years of high solar activity. Therefore, it is of great interest to study the solution of equation (14.5) for the density of source in the from (14.55) when the particles are uniformly emitted during a finite interval of time T. Putting (14.55) in (14.6), we get ([I.23], Section 63):

$$n(\varepsilon_\kappa, r, t) = \frac{N(\varepsilon_\kappa)}{4rT\pi^{3/2}\varkappa(\varepsilon_\kappa)}\begin{cases} \Gamma\left(\frac{1}{2}, \frac{r^2}{4\varkappa t}\right), & \text{at} \quad t \leqslant T, \\ \Gamma\left(\frac{1}{2}, \frac{r^2}{4\varkappa t}\right) - \Gamma\left(\frac{1}{2}, \frac{r^2}{4\varkappa(t-T)}\right), & \text{at} \quad t > T, \end{cases} \tag{14.57}$$

where Γ is the incomplete gamma function which can be expressed in terms of probability integral $\Phi(z)$.

After simple transformations. (14.57) becomes

$$n(\varepsilon_\kappa, r, t) = \frac{N(\varepsilon_\kappa)}{4r\pi T\varkappa}\begin{cases}\left[1-\Phi\left(\frac{r}{\sqrt{4\varkappa t}}\right)\right], & \text{at} \quad t\leqslant T,\\ \left[\Phi\left(\frac{r}{\sqrt{4\varkappa(t-T)}}\right)-\Phi\left(\frac{r}{\sqrt{4\varkappa t}}\right)\right], & \text{at} \quad t>T.\end{cases} \tag{14.58}$$

It is easy to show that at t >>T, equation (14.58) is the solution for the source in the form of δ -function.

An expression of the type (14.58) was used by A.A. Stepanyan [100] for determining $\varkappa$ and other mean characteristics of the flare of cosmic rays on May 4, 1960.

The results of calculations done by L.I. Dorman and L.I. Miroshnichenko [101] with the help of formula (14.58) at N = 10^{38} particles, $\varkappa = 10^{23}$ cm^2/sec, T = 10-3.16x10^7 sec, r = 0.1-4 a.u. and t = 5x10^2-3.16x10^7 sec are given below.

The calculations show that if T is small, the curve of change in concentration of solar particles of a given energy is less sensitive to the duration of emission. It is obvious from Fig. 14.28 on which curves of change in concentration of solar particles are shown for $\varkappa = 2.75 \times 10^{22}$ cm^2/sec (ε_k = 5 Gev.) and for different values of T. The calculated curve (dotted) for $\varkappa = 10^{21}$ cm^2/sec (ε_k = 0.5 Gev.) and for the source in the form of δ-function is shown for the purpose of comparison. It may be seen that for particles with ε = 5 Gev at T $\lesssim 10^3$ sec, we get a curve which practically corresponds to the case of an instantaneous source. On increasing T, the maximum of the curve gets displaced towards large values of t. While the increase in concentration is very gradual the decrease after the maximum is very sharp. As was expected from (14.7), the decrease in concentration at t>>T follows the law ~ $t^{-3/2}$, i.e., solution of diffusion equation (14.5) at large values of T does not depend on the form of injection function. It is important to underline the difference of time variation in this case from the case of δ -source. In the case of an instantaneous source, concentration quickly increases to the maximum and after this, there is gradual transition to the law of decrease ~ $t^{-3/2}$. In the case of prolonged emission, the concentration increases to the maximum more slowly but afterwards starts decreasing more quickly than according to the law $\sim t^{-3/2}$. The transition to the diffusion law of decrease takes place only at large values $t \gg T$.

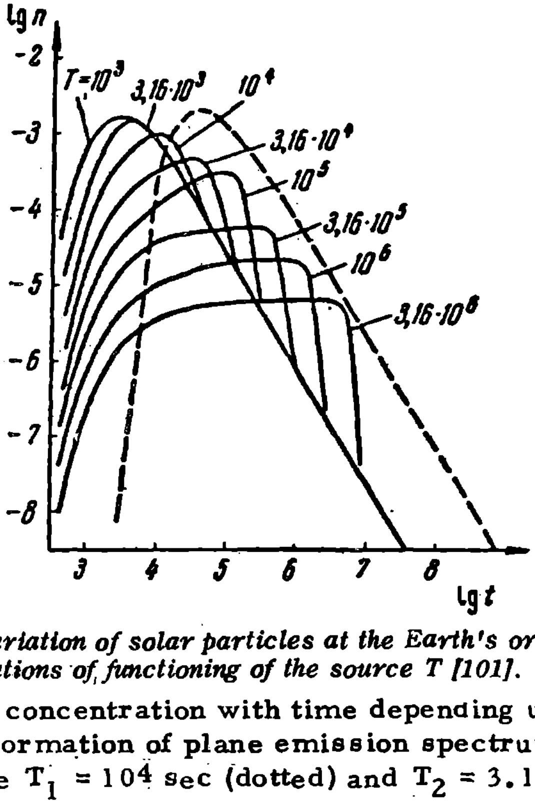

Fig. 14.28. Time variation of solar particles at the Earth's orbit for different durations of functioning of the source T [101].

Change in concentration with time depending upon the value of $\varkappa$ i.e., transformation of plane emission spectrum at different moments of time $T_1 = 10^4$ sec (dotted) and $T_2 = 3.16 \times 10^6$ sec (continuous curves), is shown in Fig. 14.29. It is characteristic that the maximum of spectrum in both the cases is attained at the same time $t = 10^4$ sec after the commencement of emission and practically corresponds to the same energy of particles ($\varkappa = 10^{22}$ cm^2/sec) but the maximum flux of particles at $T_1 = 10^4$ sec is about 300 times that at $T_2 = 3.16 \times 10^6$ sec.

The above-mentioned calculated results facilitate determination of the duration of emission of solar cosmic rays from the generation region on the basis of time variations of their intensity. For example, by applying the equation of the type (14.58) to the May 4, 1960 flare, A.A. Stepanyan [100] obtained

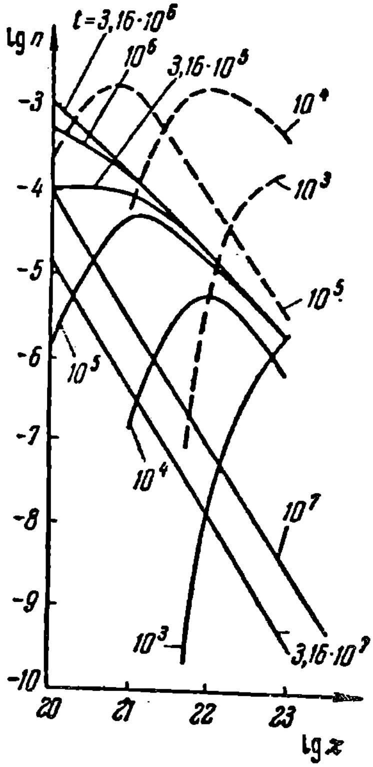

Fig. 14.29. Differential spectrum of solar particles near the Earth in the case of a prolonged source having plane emission spectrum [101].

best agreement with the observed data of Sulfur station ($R_{\min}$ = 1.1 Gv) at $\varkappa = 7 \times 10^{22}$ cm^2/sec and T = 7.5 min. Apparently, this result is not very rigid since the value of $\varkappa$ used in [100] is the average value for all particles having R $\gg$ 1.1 Gv.

As mentioned above, the experiment points out the exponential nature of injection function. In this connection, solution of equation (14.5) for an exponential source of the type (14.56) is studied in the work of L.I. Miroshnichenko [102]:

$$n(r,\, t) = \frac{N}{(2\sqrt{\pi\varkappa})^3} \int\limits_0^t \frac{e^{-\tau/T_0}}{(t-\tau)^{3/2}}\, e^{-\frac{r^2}{4\varkappa(t-\tau)}}\, d\tau. \qquad (14.59)$$

The integral (14.59) cannot be expressed into elementary functions and therefore, numerical (machine) calculations of n were done from formula (14.59) for studying the time variation and energy spectrum of solar particles. The same parameters as in calculations [101] were used here.

As was expected, the curves of time variation have a maximum which is displaced towards lesser values of t on increasing $\varkappa$ while the maximum becomes more diffused on increasing T_0 (Fig. 14.30).

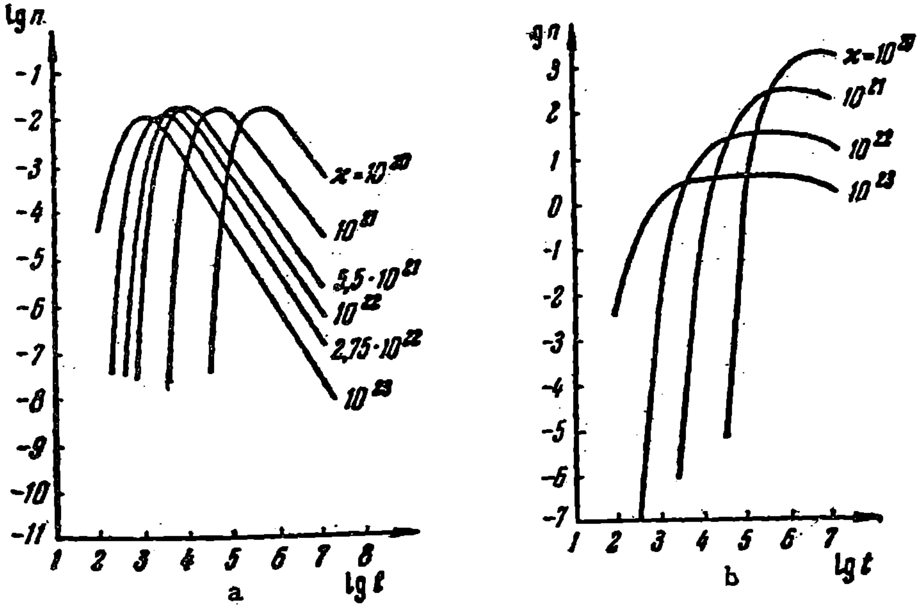

Fig. 14.30. Time variation of solar particles at the Earth's orbit in the case of an exponential source at a) $T_0 = 10^3$ sec and b) $T_0 = 10^7$ sec.

The change in the concentration of particles of different energy at the Earth's orbit due to an increase in T_0 is of great interest. It is seen from Fig. 14.31 that the concentration at any time of observation (curves for $t_1 = 10^4$ sec and $t_2 = 10^5$ sec are plotted in Fig. 14.31) practically stops increasing at large values of T_0 while the maximum is displaced towards lesser energies (from $\varkappa = 10^{22}$ cm^2/sec to $\varkappa = 10^{21}$ cm^2/sec) on transitting from t_1 to t_2. The dependence $n_{max}(T_0)$ at the Earth's orbit is shown in the same Fig. for particles having $\varkappa = 10^{20}$ cm^2/sec and $\varkappa = 10^{21}$ cm^2/sec (dotted). It is seen that at not very large values of T_0, the concentration of particles at the time of maximum, changes proportionately to T_0. The growth $n_{max}(T_0)$ becomes slower in the region of very large values of T_0.

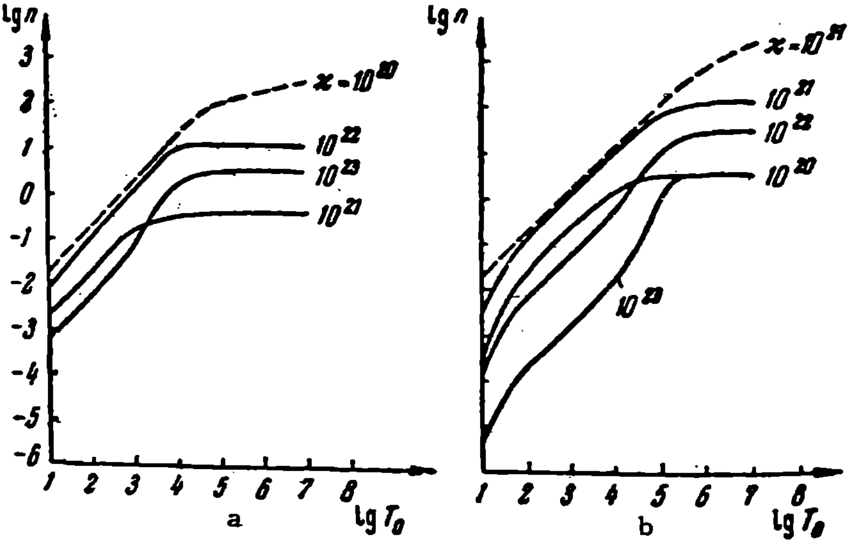

Fig. 14. 31. Change in the concentration of solar particles of different energy at the Earth's orbit at a) $t_1 = 10^4$ sec and b) $t_2 = 10^5$ sec. The dependence n_{max} (T_0) is shown by dotted curves.

Spectra of solar particles at $t_1 = 10^4$ sec and $t_2 = 10^5$ sec for different values of T_0 and by assuming the emission spectrum to be plane, are shown in Fig. 14. 32. The shape of spectrum expected at the Earth's orbit slightly depends on T_0 but it practically does not depend on T_0 at $T_0 > 10^5$ sec (in any case, at the selected values of t_1 and t_2).

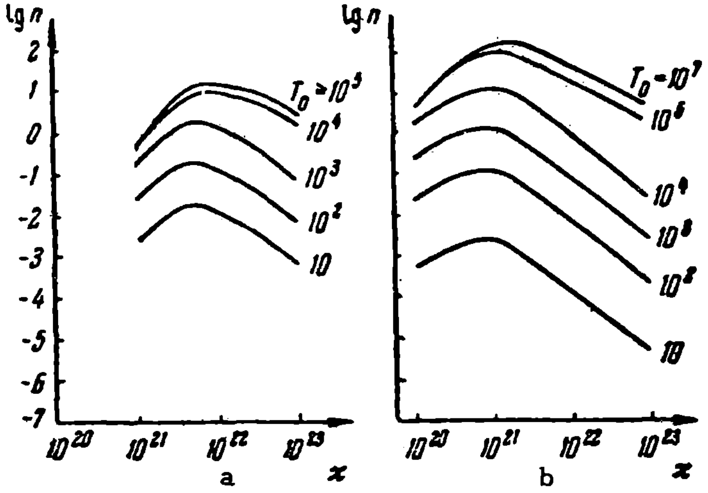

Fig. 14. 32. Spectra of solar particles near the Earth in the case of plane spectrum of the source: a) $t_1 = 10^4$ sec; b) $t_2 = 10^5$ sec.

The dependence of the time of appearance of maximum concentration of solar particles on T_0 is shown in Fig. 14.33. It is seen that the dependence $t_{max}(T_0)$ is very weak at low values of $\varkappa$ and T_0. However, significant growth of t_{max} is observed on increasing $\varkappa$ and T_0. Thus, for example, t_{max} for particles of very high energy ($\varkappa \simeq 10^{23}$ cm^2/sec) changes by about three orders on changing T_0 from 10 to 10^7 sec.

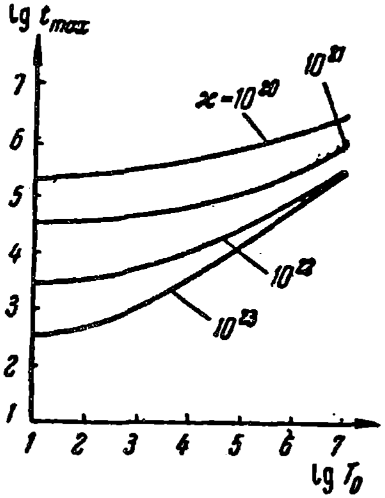

Fig. 14.33. Dependence of the time of appearance of maximum concentration of solar particles on T_0.

In order to explain the above-mentioned peculiarities of time variation of solar particles, let us consider the asymptotic behavior of integral from (14.59) for two extreme cases.

1) T_0 is small. Introducing the notations

$$\frac{N}{(2\sqrt{\pi\varkappa t})^3} = A, \qquad \frac{\exp\left(-\frac{r^2}{4\varkappa(t-\tau)}\right)}{(t-\tau)^{3/2}} = \varphi(t-\tau),$$

(14.59) can be written in the form

$$n = A\int_0^t e^{-\tau/T_0}\varphi(t-\tau)\,d\tau. \tag{14.60}$$

Since the exponent $e^{-\tau/T_0}$ at low values of T_0 decreases very quickly, the function Q($t-\tau$) can be approximately replaced by its value at the point $\tau = 0$ and upper limit of integration can be put equal to ∞. Then, the relation (14.60) takes the form

$$n = A\varphi(t)T_0, \tag{14.61}$$

from which it follows that $n_{max} \sim T_0$ in accordance with the dotted curves of Fig. 14.31, in the region of low values of T_0. Moreover, differentiating (14.61) with respect to t and equating the derivative to zero, we get $\partial n/\partial t = AT_0 \cdot \partial\varphi/\partial t = 0$, i.e., $\partial\varphi/\partial t = 0$ from where it can be concluded (without calculating t_{max} explicitly) that t_{max} practically will not depend on T_0 in the region of low values of T_0. This result does not contradict the curves of Fig. 14.33 at low values of T_0.

2) T_0 is large. In this case, the index $-\tau/T_0$ of the exponent will be small at every value of τ. Taking it into account, let us expand $e^{-\tau/T_0}$ into a series. Then, (14.59) takes the form

$$n = A\int_0^t \varphi(t-\tau)\left(1 - \frac{\tau}{T_0} + \frac{1}{2}\frac{\tau^2}{T_0^2} - \frac{1}{6}\frac{\tau^3}{T_0^3} + \ldots\right)d\tau =$$

$$= A\int^t \varphi(t-\tau)\,d\tau + A\int_0^t \varphi(t-\tau)\,f\left(\frac{\tau}{T_0}\right)d\tau, \tag{14.62}$$

where $f\left(\frac{\tau}{T_0}\right) = -\frac{\tau}{T_0} + \frac{1}{2}\cdot\frac{\tau^2}{T_0^2} - \frac{1}{6}\cdot\frac{\tau^3}{T_0^3} + \ldots$ Firstly, it is seen from (14.62) that the dependence of concentration of particles on T_0 at the time of maximum is more complicated at large values of T_0 than at low values of T_0. It corresponds to the form of curves $n_{max}(T_0)$ shown in Fig. 14.31 for large values of T_0. Moreover, owing to the presence of two terms in (14.62) one of which depends only on t and the other on t and T_0, it can be concluded (without calculating t_{max} explicitly) that t_{max} will depend on T_0 at large values of T_0 in accordance with the curves shown in Fig. 14.33.

Let us now study the behavior of integral (14.59) at large values of t ($t \to \infty$). Differentiating (14.59) with respect to t:

$$\frac{\partial n}{\partial t} = -\frac{1}{T_0}n + \frac{N}{(2\sqrt{\pi \varkappa t})^3}\exp\left(-\frac{r^2}{4\varkappa t}\right). \tag{14.63}$$

and solving the equation (14.63) with respect to n (expansion of $e^{-r^2/4\varkappa t}$ into a series is used here), we get

$$n = AT_0 t^{-3/2} + AT_0\left(\frac{3}{2}T_0 - \frac{r^2}{4\varkappa}\right)t^{-5/2} + \\ + T_0 A\left[T_0\left(\frac{3}{2}T_0 - \frac{r^2}{4\varkappa}\right)\frac{5}{2} + \frac{1}{2}\frac{r^2}{16\varkappa^2}\right]t^{-7/2} + \dots, \tag{14.64}$$

from which it is seen that on increasing t, the dependence n(t) asymptotically approaches the law $\sim t^{-3/2}$.

Thus, the shape of the curves of time variation at large values of t is less sensitive to the value of T_0 and satisfies the equation of isotropic diffusion in an infinite space for the case of instantaneous source. On the other hand, two other important characteristics of solar cosmic rays, namely, time of appearance of the maximum t_{max} and concentration of particles n_{max} at this moment of time, significantly depend on T_0. It facilitates determination of the value of T_0 from the experimental data if the differential spectrum of solar particles is measured during a long interval of time and within a wide range of energies.

It is assumed by Nagashima [103] that F can be approximated by one of the following three types of functions:

$$\text{I. } F = N\delta(r)\delta(R - R_*)\delta(t). \tag{14.65}$$

$$\text{II. } F = N\delta(r)f(R)\delta(t). \tag{14.66}$$

$$\text{III. } F = N\delta(r)\begin{Bmatrix}\delta(R - R_*)\\ f(R)\end{Bmatrix}\varphi(t)\varphi(-t + t_*), \tag{14.67}$$

where δ is the delta function while $\varphi(x) = 1$ at $x \geqslant 0$ and $\varphi(x) = 0$ at $x < 0$.

The type I function corresponds to instantaneous emission of monochromatic beam of particles of rigidity R_*. The type II refers to the case of instantaneous injection of particles with continuous rigidity spectrum and the type III to the case of continuous and prolonged emission of cosmic rays with monochromatic or continuous rigidity spectrum during injection period Δt_s.

As far as boundary conditions are concerned, it is assumed in [103] that the diffusion region extends to a distance of r_0 from the source while Λ is infinite beyond this region. To simplify the analysis, the ratio $\xi = r_b/r_0$ has been introduced where r_b is the distance of the observation point from the source. Time t is counted from the moment of maximum intensity t_{max} and is expressed in terms of the units of interval during which the maximum intensity reduces by 2 times. In subsequent discussion, this rated time is denoted by τ. The intensity is graded in terms of the maximum intensity. Periods of increase and decrease of intensity are known as premaximum and postmaximum periods. Let us assume that the particles are emitted by a source of type II with the power rigidity spectrum and they propagate in the medium of diffusion coefficient $\varkappa \sim R^{\alpha}$. We will also assume that solar cosmic rays generate secondary particles in the terrestrial atmosphere with the integral generation multiplicity factor $m \sim R^k$. In this case, as shown in [103], the intensity observed at the Earth's surface will almost be the same as in the case F of type I, i.e., the source of type II is equivalent to source of type I within the limits of the above-made assumptions.

Injection period Δt_s is the only factor that has an effect on the shape of the intensity-time curve. Therefore, a comparison of the observed intensity with the calculated curve facilitates determination of the value of Δt_s. In [103], the diffusion coefficient has the form $\varkappa = A(\Delta t_s) r^2/\tau$ where r is the distance of observation point from the source and A is weakly changing function of Δt_s. From here, it is possible to evaluate $\varkappa$ with an accuracy up to some constant factor even if we don't have any information about Δt_s. The total number of particles, emitted during injection, also hardly depends on Δt_s.

Existence of a finite limit on diffusion region complicates the dependence of intensity on time. According to calculations [103], deviation of curve at $\xi = 1/2$ for premaximum period from the curve for the case of three-dimensional diffusion in an infinite medium is negligible. Thus, if it can be established that $\xi < 1/2$, it would be possible to neglect the effect of the finite limit. The corresponding deviation, caused by the existence of finite limit, for the postmaximum period is significant even if the value of ξ is approximately equal to 1/2.

14.9. Consideration of motion of magnetic irregularities. If the irregularities of magnetic field, scattering solar cosmic rays, move radially from the Sun with velocity u, the equation of diffusion by convection of particles takes the form:

$$\frac{\partial n}{\partial t} = \varkappa \nabla^2 n - \mathrm{u}\,\mathrm{grad}\, n + F(r, t); \quad n(r, 0) = 0 \qquad (14.68)$$
$$(0 < r < \infty, \quad t > 0).$$

Taking $F(r, t) = N\delta(r)\,\delta(t)$, we get the solution of (14.68) in the form

$$n(r, t) = \frac{N}{(2\sqrt{\pi\varkappa t})^3} \exp\left[-\frac{(r - ut)^2}{4\varkappa t}\right]. \qquad (14.69)$$

Obviously, in the case of $ut \sim r$, the concentration of solar particles at a fixed distance decreases more quickly than in the static case ($u = 0$). The moment of attaining the maximum intensity will also depend on the rate of motion of irregularities [I. 2]:

$$t_{\max} = \frac{3\varkappa}{u^2}\left[\sqrt{1 + \frac{u^2 r^2}{9\varkappa^2}} - 1\right] = \frac{r^2}{6\varkappa}\left[1 - \frac{1}{4}\frac{u^2 r^2}{\varkappa^2} + \frac{1}{8}\frac{u^4 r^4}{\varkappa^4} - \ldots\right]. \qquad (14.70)$$

At $r^2u^2/\varkappa^2 \ll 1$, the expression (14.69) changes into (13.7). Given below are the results of calculation obtained by L.I. Dorman and L.I. Miroshnichenko [87] for concentration of solar cosmic rays as a function of time and distance from the Sun at $N = 10^{38}$ particles, $\varkappa = 10^{20}$-10^{23} cm^2/sec, u = 0-3.16x10^8 cm/sec, r = 0.1-3 a.u. and t = 10^3-10^7 sec.

The dependence of $\varkappa$ on the energy of particles must, with the passage of time, lead to enrichment of their spectrum with low-energy particles. This is confirmed by the analysis of data on a number of flares [I. 3; I. 23; 33]. On the other hand, the spectrum of solar particles in many cases [I. 35; III. 137] apparently has the tendency towards an increase in rigidity with the passage of time. Possibly, in the works [I. 35; III. 137] the results are partially explained by the convection of particles due to radial motion of irregularities from the Sun. Calculations [87] showed that the generation spectrum of solar cosmic rays in this case undergoes significant changes in the region of low energies at sufficiently large values of t. It is obvious from Fig. 14.34, where the dpendence of concentration of solar particles at the Earth's orbit on $\varkappa$(i.e., on their energy) is shown for u = 0 (continuous curves) and u = $3.16\mathrm{x}10^7$ cm/sec (dotted curves).

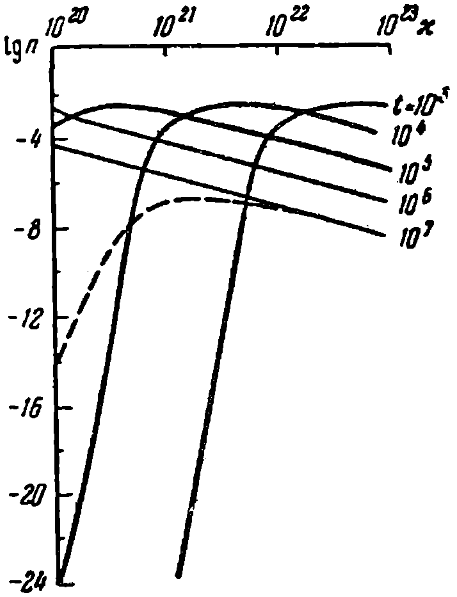

Fig. 14. 34. Dependence of the concentration of solar particles at the Earth's orbit on their energy for u = 0 (continuous curves) and u = 3.16x 10^7 cm/sec (dotted curve).

The change with time in the concentration of solar particles of different energies at the Earth's orbit is shown in Fig. 13.35 where the continuous curves are plotted without considering the motion (u = 0) and the dotted curves, for u = $3.16\mathrm{x}10^7$ cm/sec. In the case of particles of the same energy ($\varkappa$= 10^{22} cm^2/sec), their concentration at different values of u will change in accordance with Fig. 14.36 where continuous curves refer to the Earth's orbit and the dotted curve, to r = 3 a.u. As is obvious from Fig. 14.36, the motion of irregularities has the maximum effect on particles of nonrelativistic energies ($\varkappa$= 10^{20} cm^2/sec)

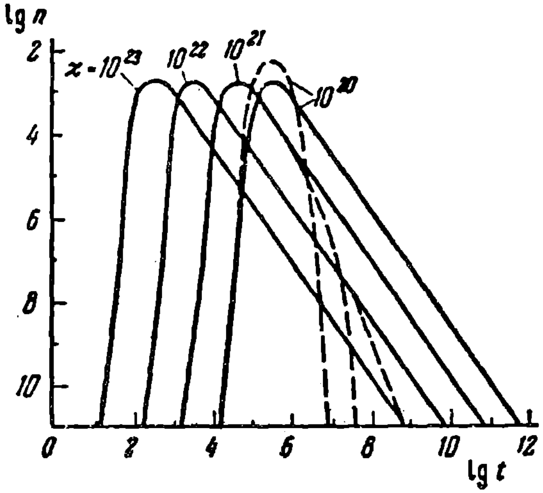

Fig. 14. 35. Change with time in the concentration of solar particles of different energies at the Earth's orbit for $u = 0$ (continuous curves) and $u = 3.16 \times 10^6$ cm/sec (dotted curves).

by displacing the time of maximum intensity towards lesser values of t in accordance with (14.70). In this case, the rate of decrease at sufficiently large values of t increasees significantly on increasing u.

These results of calculation apparently do not give a base to conclude about the exponential nature of decrease in the intensity of solar particles but it is beyond any doubt that, owing to radial motion of magnetic irregularities from the Sun, the intensity on the Earth decreases more quickly than according to law $\sim t^{-3/2}$ especially for low-energy particles and at sufficient ly large values of t.

The motion of magnetic irregularities does not have any effect on the spectrum of solar particles in the beginning of the outburst and during the initial period of decrease of intensity at the Earth's orbit. However, this effect can be significant at later stages of an event especially for particles which give rise to polar cap absorptions of short radio waves. It is difficult to detect this effect experimentally due to the possible existence of a variable background of low-energy particles in the inter-planetary space (see Section 11) and due to unsuitability of diffusion approximation at energies $\varepsilon_k < 100$ mev.

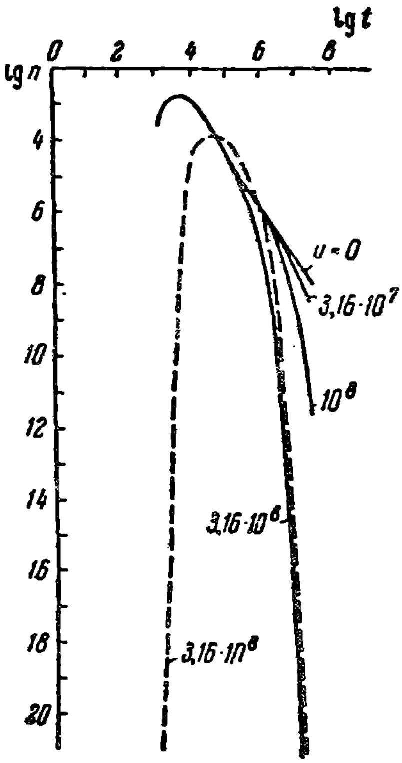

Fig. 14. 36. Change with time in the concentration of solar particles at various velocities of magnetic irregularities. Continuous curves - for $r = 1$ a.u.; dotted curve - for $r = 3$ a.u.

15. SOME MODIFICATIONS OF THE DIFFUSION MODEL

For explaining the limits of applicability of diffusion approximation, it is important to consider some other limitations as well (in addition to those mentioned in Section 14) imposed by the interplanetary magnetic field (for example, anisotropic diffusion) and properties of the source (finite dimensions, position on the solar disk, etc.).

15.1 Anisotropic diffusion. Let us consider a point, instantaneous source situated at the origin of coordinates. Putting $\beta = 1$ and assuming diffusion to be one-dimensional, we get the solution of (14.27) in the form

$$n(R, x, t) = \frac{N(R)}{2\varkappa(R)t} e^{-\frac{x}{\varkappa \underset{\delta}{+} t}}. \tag{15.1}$$

This result is important for quantitatively explaining the observed transformation of the spectrum of solar particles with time and for explaining the dependence $\varkappa(R)$.

Diffusion of solar particles in the presence of quasiradial field can be the cause of displacement of maximum outburst for flares of different types. It follows from equation (14.8), that the duration of time interval from the commencement of the outburst to the maximum at a fixed distance from the source is inversely proportional to diffusion coefficient: $t_{max} \sim \varkappa^{-1}$ and consequently, to the transport range: $t_{max} \sim \Lambda^{-1}$. Taking this into consideration, it is apparently possible to understand the displacement of t_{max} of type B and C outbursts with respect to t_{max} of type A outburst in the light of the concepts of the twisted interplanetary field. As mentioned in Section 10, type A outbursts are caused by the flares on the western limb of the Sun when the twisted lines of force of the regular interplanetary field directly connect the Earth to the active region responsible for the flare. Outbursts of type B are caused by chromospheric flares near the central meridian of the Sun when the direct magnetic connection between the Earth and the corresponding active region can be absent. Assuming that solar particles in the first case diffuse parallel to the lines of force and in the second case, perpendicular to them, we get the ratio:

$$\frac{t_{\parallel}}{t_{\perp}} = \frac{\Lambda_{\perp}}{\Lambda_{\parallel}}, \qquad (15.2)$$

where $t_{\parallel}$ and $t_{\perp}$ are the times of maxima for outbursts of type A and B respectively and $\Lambda_{\parallel}$ and $\Lambda_{\perp}$ are the mean free paths parallel and perpendicular to the field respectively. On the other hand, according to L.I. Dorman [51], the ratio of these mean free paths is equal to

$$\frac{\Lambda_{\perp}}{\Lambda_{\parallel}} = \frac{1}{1+\omega_0^2\tau^2}, \qquad (15.3)$$

from which, for protons of not very large energies, we get

$$\frac{\Lambda_{\perp}}{\Lambda_{\parallel}} = \frac{\varepsilon^2}{e^2H_0^2\Lambda_{\parallel}^2} \qquad (15.4)$$

With the help of (15.2) and (15.4), it is possible to find out the intensity of regular component of the interplanetary field:

$$H_0 = \frac{\varepsilon}{e\Lambda}\sqrt{\frac{\Lambda_\parallel}{\Lambda_\perp}} = \frac{\varepsilon}{e\Lambda_\parallel}\sqrt{\frac{t_\perp}{t_\parallel}}. \qquad (15.5)$$

A similar approach was made in the work of B. M. Vladimirskii [104] to two groups of flares: flares of the first group occurred in the regions responsile for Forbush reduction (diffusion parallel to the lines of force) while flares of the second group, in the regions not related to Forbush reduction (diffusion perpendicular to the field). The obtained ratio $t_\perp/t_\parallel$ is approximately equal to 3. If the value of about 4×10^{11} cm, found out by N.S. Kaminer et al. [I. 35] for the May 4, 1960 flare, is taken for $\Lambda_\parallel$ and if the energy of particles is taken to be about 3 Gev, we get $H_0 \sim 4 \times 10^{-5}$ gauss = 4 γ which is well in agreement with the results of direct measurements (see Section 13.2).

The effect of the radial interplanetary field on the diffusion of solar cosmic rays was also studied by V.I. Shishov [50] (see Section 16.2).

15.2 Source of finite dimensions. As suggested by Kawabata et al. [105], a cosmic-ray flare can develop in the following way: acceleration of particles to the energies of cosmic rays takes place in the region of solar flare; the accelerated particles are captured by magnetic fields in the solar region in a volume of radius $r_0 \approx 0.2$-0.4 a.u.; particles emitted from this volume increase the intensity of cosmic rays in shock zones on the Earth's surface; a small fraction of particles is reflected by the external trapping field surrounding the Sun and the Earth which leads to isotropization of the beam. Such a model of flare leads to the following heterogeneous diffusion equation:

$$\left.\begin{aligned}
&\frac{\partial n}{\partial t} = \varkappa\left[\frac{\partial^2 n}{\partial r^2} + \frac{2}{r}\frac{\partial n}{\partial r}\right], \quad 0 < r, \quad t < +\infty, \\
&n(r, 0) = \begin{cases} n_0 \equiv \text{const} & \text{at} \quad 0 \leqslant r < r_0, \\ 0 & \text{at} \quad r_0 < r < +\infty, \end{cases}
\end{aligned}\right\} \qquad (15.6)$$

where r is the radius vector in the spherical system of coordinates. The solution of equation (15.6) can be represented in the form

$$n(r, t) = \frac{n_0}{2}\left[\Phi\left(\frac{r-r_0}{2\sqrt{\varkappa t}}\right) - \Phi\left(\frac{r-r_0}{2\sqrt{\varkappa t}}\right)\right] + \\ + \frac{n_0}{r}\sqrt{\frac{\varkappa t}{\pi}}\left[\exp\left(-\frac{(r-r_0)^2}{4\varkappa t}\right) - \exp\left(-\frac{(r+r_0)^2}{4\varkappa t}\right)\right], \quad (15.7)$$

where Φ (z) is the probability integral.

Analyzing the data of May 4, 1960 flare, McCracken [4] arrived at the conclusion that the delay of the effect at different stations can be explained by the model in which the source occupies a volume of radius about 0.25 a.u. On the basis of observations from the Earth, the angular dimension of this source will be $\Phi_{\perp} \approx 30°$. Such a value of angular dimension of the source was used by N.S. Kaminer [1 06] for calculating shock zones. The analysis of experimental data, made by Firor [I. 7], shows that the value $\Delta\Phi_{\perp} \sim 30°$ mostly corresponds to reality. This conclusion is true, in particular, for the February 23, 1956 flare [I. 2].

Using the model of injection of particles at a distance of 0.25 a.u. from the Sun, it is necessary to take into account their collective interaction right up to this distance. However, as mentioned by McCracken [4], on the basis of this model, it is impossible to explain large pitch angles of particles observed during May 4, 1960 flare as well as the ratio between the densities of the energy of interplanetary magnetic field and solar cosmic rays.

15.3 Dependence of the effect of flares on their heliocoordinates. The elementary diffusion model cannot, in particular, explain the dependence of the amplitude and time scale of cosmic-ray outbursts on heliolongitude of corresponding solar flares. For quantitative explanation to this dependence as well as for describing the concluding phase of a flare of solar cosmic rays, it is necessary to consider the possible changes in diffusion coefficient on increasing the distance from the Sun and the dependence of diffusion coefficient on direction.

Existence of the regularized radial magnetic field in the solar system makes the diffusion of particles anisotropic and therefore, $\varkappa$ in the general case is a tensor of second order. As the first approximation, G. F. Krymskii [94] assumed that $\varkappa_{\parallel}(r) = a\varkappa_{\perp}(r)$ where $\varkappa_{\parallel}$ and $x_{\perp}$ are diffusion coefficients along and perpendicular to the radius while $\varkappa_{\parallel} \sim r^{\beta}$ where $\beta \geqslant 0$. The process of injection of particles from the Sun is considered to be instantaneous and taking place at one place.

Under these assumptions, the time variation of solar particles was calculated by Krymskii [94] at various distances from the Sun and at various angles between the radius vectors of observation point and the point of particle-emission. Such a calculation can be used, for example, for analyzing the outbursts of cosmic rays due to flares on the invisible hemisphere of the Sun, for comparing the outbursts on the Earth and at significant distances from it, etc. An analytical solution of this problem is described below.

In the spherical system of coordinates with polar axis passing through the ejection-point of particles, the concentration equation has the form:

$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\varkappa_{\parallel}\frac{\partial n}{\partial r}\right) + \frac{\varkappa_{\perp}}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial n}{\partial\theta}\right) \qquad (15.8)$$

At the initial condition

$$n(r,\theta)\Big|_{t=0} = \frac{N}{r^2\sin\theta}\,\delta(r - r_{\odot})\,\delta(\theta) \qquad (15.9)$$

following solution of (15.8) was obtained in [94]:

$$n(r,\theta,t) = (r_{\odot}r)^{-\frac{1+\beta}{2}} r_{\odot}^{\beta}\frac{N}{(2-\beta)\varkappa_{\parallel}^{\odot}t}\exp\left[-\frac{r^{2-\beta}+r_{\odot}^{2-\beta}}{(2-\beta)^2\varkappa_{\parallel}^{\odot}t}r_{\odot}^{\beta}\right]\times$$

$$\times\sum_{k=0}^{\infty}\left(k+\frac{1}{2}\right)P_k(\cos\theta)\,\bar{I}_{\nu_k}\left[\frac{2(r_{\odot}r)^{\frac{2-\beta}{2}}r_{\odot}^{\beta}}{(2-\beta)^2\varkappa_{\parallel}^{\odot}t}\right]. \qquad (15.10)$$

Here I_{ν_k} is the Bessel function with imaginary argument, P_k is Legendre polynomial, $\varkappa_{\parallel}^{\odot}$ is the radial coefficient at $r = r_{\odot}$ and $\nu_k=[(1+\beta)^2 - 4(\varkappa_{\perp}/x_{11})\ k\ (k+1)]^{1/2} / (2-\beta)$.

The expression (15.10) gives the solution of this problem for the index β within the limits $0 \leq \beta \leq 2$. The results of Section 14.6 show that $\beta \lesssim 1$. Equation (15.10) can be tabulated on electronic computers.

15.4 Anistropy of solar particles in diffusion approximation. A beam of particles $\varkappa$dn/dr, directed from the Sun, must be observed on the Earth's orbit some time after the chromospheric flare. It leads to anistropy whose amplitude, by taking into account (14.7), will be determined by the relation

$$\eta = \frac{\varkappa\, dn/dr}{nv} = \frac{r}{2tv}. \qquad (15.11)$$

Let us consider the following problem in order to evaluate the degree of anisotropy of a beam of solar particles in diffusion approximation by taking into account the angular distribution of their velocities. Let N particles be emitted from a point, instantaneous source, situated in an isotropic infinite medium, at time $t_0 = 0$. Then at $t > t_0$, there will be $n(r, t, \mu)\, d\mu\, dr$ particles in the interval between r and r + dr, the velocities of which will make an angle of θ with the direction of r and therefore, $\cos\theta$ lies between μ and $\mu + d\mu$ ($\mu = \cos\theta$). From this, we get

$$n(r, t) = dr \int_{-1}^{+1} n(r, t, \mu)\, d\mu. \qquad (15.12)$$

Let us further assume that the dependence of n on t can be expanded as

$$n(r, t, \mu) = \sum_{l=0}^{\infty} \mu^l n_l(r, t) = n_0(r, t) + \mu n_1(r, t) + \mu^2 n_2(r, t) + \ldots \qquad (15.13$$

and the dependence on angle is very weak because of which we have to limit ourselves with the first two terms of the expansion. Then, the first term will define the concentration of isotropic beam of solar particles and the second term, the concentration of anisotropic beam. The higher-order terms will describe the minute details of distribution of particles and therefore, can be neglected [43].

Determining the functions n_0 and n_1 which do not depend on μ and putting them in (15.13), we get [87]

$$n(r, t, \mu)=\frac{1}{2}\frac{N}{(2\sqrt{\pi\varkappa t})^3}e^{-\frac{r^2}{4\varkappa t}}[1+\eta\mu], \qquad (15.14)$$

where $\eta = 3r/2tv$ is the amplitude of relative anisotropy for the beam of solar particles, the velocities of which make an angle ($\mu = \cos\theta$) with the direction of r. The value of η in (15.14) is 3 times more than the estimated value (15.11). In this case, in contrast to (14.20), anisotropy must be observed not in the form of an exponential cofactor but in the form of an additional term depending on the value of θ. It is important to mention that under the assumptions made while deriving (15.11) and (15.14), the amplitude of anisotropy does not depend on Λ and is inversely proportional to velocity of the particles and time from the commencement of the flare.

Anisotropic beam of solar particles of concentration given by equation (15.14) attains the maximum at a time determined by the following relation:

$$t_{\max}=\frac{r}{2\varkappa v}\{(rv-15\varkappa\mu)+\sqrt{(rv-15\varkappa\mu)^2+36rv\varkappa\mu}\}. \qquad (15.15)$$

Equations (15.14) and (15.15) can be verified experimentally by measuring anisotropy of solar cosmic rays in the interplanetary space.

15.5 Time variation of solar particles and geometry of diffusion process. As was shown in previous Sections, solar protons injected into the interplanetary medium diffuse to the Earth by scattering at the "frozen" magnetic irregularities which were uniformly distributed in the interplanetary space. On the other hand, it is known that solar corona does not always have spherical shape and that the magnetic field of solar wind is twisted into Archimedean spiral due to rotation of the Sun. In this connection, Boldt [107] made an attempt to show that the observed moment of maximum of the time variation of solar cosmic rays is an ambiguous indicator of the geometry of diffusion process.

The distribution function for particles, diffusing between scattering centers of a passive medium, corresponds to Smolukhovskii's generalized diffusion equation which is of the form

$$\frac{\partial n}{\partial t}+\nabla[nu+J]=0, \tag{15.16}$$

where u is the drift velocity of the medium (i.e., velocity of the solar wind) and $J = -\varkappa\nabla n$ while $\varkappa = \varkappa_{ij}$ is the diffusion tensor (i, j = 1, 2, 3) consisting of 9 terms. Since the velocity of diffusing protons ($\lesssim 10^{10}$ cm/sec) is more by about 3 orders than the velocity of solar wind, it can be assumed that u = o.

Let us consider two extreme cases: 1) three-dimensiona isotropic diffusion characterized by diffusion coefficient $\varkappa_{ij} = \varkappa_3\delta_{ij}$ (δ_{ij} is the delta function) and 2) one-dimensional diffusion defined by diffusion coefficient $\varkappa_{ij} = 0$ at $(i, j) \neq (1.1)$ and $\varkappa_{11} = \varkappa_1$. Let us assume that the particles were emitted at the moment $t_o = 0$ at the origin of coordinates in an infinite medium. As far as the physical situation at the absorbing boundary r_o is concerned, the solution for infinite medium is approximately valid [I. 61] under the condition that the observations are restricted in space and time, $|r| < r_o$ and $t \leqslant 10^{-1}(r^2{}_o/\varkappa)$.

In the case of three-dimensional isotropic diffusion, solution of diffusion equation (15.16), satisfying these limitations, is of the form

$$n_3=(4\pi\varkappa_3 t)^{-3/2}\exp\left(-\frac{r^2}{4\varkappa_3 t}\right), \tag{15.17}$$

and in the case of one-dimensional diffusion

$$n_1=(4\pi\varkappa_1 t)^{-1/2}\exp\left(-\frac{r^2}{4\varkappa_1 t}\right). \tag{15.18}$$

The solutions of equations (15.17) and (15.18) are simil in form to the corresponding solutions of the problem of causal straying of particles with velocity v and step length L [41]. For the case of three-dimensional diffusion, we get

$$n_3=\left(\frac{4}{3}\pi L_3 vt\right)^{-3/2}\exp\left(-\frac{r^2}{{}^4/_3 L_3 vt}\right). \tag{15.19}$$

In the one-dimensional case , the solution of the problem of causal strayings has the form

$$n_1 = (4\pi L_1 vt)^{-1/2} \exp\left(-\frac{r^2}{4L_1 vt}\right). \qquad (15.20)$$

Comparing (15.19) with (15.17) and (15.20) with (15.18) we get

$$\varkappa_3 = \frac{1}{3} vL_3, \qquad (15.21)$$

$$\varkappa_1 = vL_1. \qquad (15.22)$$

For a given observation point r, from (15.19) and (15.20) , we find that the intensity becomes maximum at the moment t_{max} defined by the relation

$$t_{max} = \frac{r^2}{2vL}. \qquad (15.23)$$

Putting (15.21) and (15.22) in (15.23) , the relation for t_{max} can be rewritten in a form which facilitates better differentiation of two extreme cases. For isotropic diffusion (15.21), we get

$$t_{max} = \frac{1}{6}\left(\frac{r}{r_0}\right)^2 \frac{r_0^2}{\varkappa_3}. \qquad (15.24)$$

In the one-dimensional case,

$$t_{max} = \frac{1}{2}\left(\frac{r}{r_0}\right)^2 \frac{r_0^2}{\varkappa_1}. \qquad (15.25)$$

It can be seen from this that when $\varkappa_1 = \varkappa_3$, the intensity in the case of three-dimensional diffusion becomes maximum three times earlier than in the case of one-dimensional diffusion. Moreover the exit of particles beyond r_0 becomes significant at $t \ll t_{max}$ for one-dimensional diffusion but at $t > t_{max}$ for isotropic diffusion. According to the above-mentioned limitations imposed on the idealized solutions, such a situation can exist when $(r/r_0)^2 \gg 1/5$. On fulfilling this condition, observations on the Earth will be comparatively insensitive to one-dimensional component of the diffusion process. In other words, the role of one-dimensional diffusion cannot be observed under present conditions of observations.

15.6 Diffusion model for the initial stage of a flare.

In the work of Reid [108] , an attempt has been made to explain the initial anisotropic phase of a cosmic-ray outburst on the basis of the following model.

Protons from a flare diffuse along the Sun's surface in a thin layer of its atmosphere (two-dimensional diffusion) and gradually impregnate into a tube of the lines of force of the interplanetary field. One of these tubes connect the Sun's surface with the Earth's magnetosphere. As the density U of protons near the base of solar-terrestrial magnetic tube increases on the solar surface, the flux of protons on the Earth will also increase by remaining anisotropic.

The region of solar atmosphere, where the diffusion takes place, is considered to be thin as compared to the dimensions of the Sun and therefore, the problem can be solved with the help of the equation of two-dimensional diffusion. Thus, Reid's model radically differs from the model of Lüst and Simpson [1.3] who, for explaining the delay of particles from the February 23, 1956 flare, studied diffusion through a spherical volume extending up to $\sim 50\ r_{\odot}$.

Let us now determine the surface density U of particles at a point situated on the solar disk at a distance r from the place of flare. Let us also assume that the rate of filling of a given tube of force by particles is proportional to surface density near its base. Had there been no leakage of particles from the internal corona, the corresponding diffusion would be of the form

$$\frac{\partial U}{\partial t} = a^2 \nabla^2 U, \tag{15.26}$$

where ∇^2 is the two-dimensional operator $(\partial^2/\partial x^2 + \partial^2/\partial y^2)$. If N particles are instantaneously liberated at $r = 0$ and $t_0 = 0$ the corresponding solution of equation (15.26) will be

$$U = \frac{N}{4\pi a^2 t} \exp\left(-\frac{r^2}{4a^2 t}\right). \tag{15.27}$$

If it is assumed that k particles are lost at the given point in unit time, the equation (15.26) takes the form

$$\frac{\partial U}{\partial t} = a^2 \nabla^2 U - kU. \tag{15.28}$$

This equation has the solution

$$U = \frac{N}{4\pi a^2 t} \exp\left(-\frac{r^2}{4a^2 t} - kt\right). \qquad (15.29)$$

In these equations, a^2 is the diffusion coefficient whose physical meaning will be discussed later. In subsequent discussion, it is assumed that the leakage of particles from the solar atmosphere takes place only in the tubes of force of the interplanetary magnetic field.

If all the tubes have similar configuration, the observed flux of particles will be simply proportional to the total number of particles in a tube. This assumption is of great significance for analyzing the anisotropic stage of the September 28, 1961 flare.

The rate of filling of a tube of force, connecting the Sun and the Earth, is proportional to the surface density U of particles near the base of the tube at a certain moment τ before observation, where τ is the time of rectilinear propagation of particles from the Sun to the Earth at a suitable velocity.

Basing on these assumptions, Reid obtained the relation

$$F'(t) = AU(t'), \qquad (15.30)$$

where F' (t) is the rate of increase of flux with time at the moment t, A = const and $t' = t - \tau$. It follows from equation (15.30) that

$$\ln[t'F'(t)] = \ln\frac{AN}{4\pi a^2} - \frac{r^2}{4a^2 t'} - kt'. \qquad (15.31)$$

This relation shows that at low values of t' (i.e., for the anisotropic phase of a flare), the graph of ln[t'F'(t)] as a function of 1/t' is a straight line with an inclination $-r^2/4a^2$. If other factors, for example, the leakage of protons from the tube, are neglected, this dependence at later moments of time must change proportionately to t' with inclination - k.

Analysis of data [I.23] for the September, 28, 1961 flare shows that the linear dependence, predicted by formula (15.31) at low values of t', is observed during the whole of the outburst of particles with $\mathcal{E}_k$ = 330 - 600 Mev and right up to 1/t' = 0.75 hrs^{-1} for particles with $\mathcal{E}_k$ = 130-330 Mev. This sudden change in inclination at 1/t' = 0.75 hrs^{-1} for particles of lesser energies approximately corresponds to the moment of time at which good conformity of data with the model of three-dimensional diffusion was observed by Bryant et al. [I. 23].

Let us define r as the radial distance from the place of flare to the base of the tube of force related to the Earth and assume that the solar atmosphere can be considered to be plane. This latter approximation is apparently disturbed at large values of r since the internal corona is, as a matter of fact, a spherical shell rather than a plane. The maximum possible value of r is equal to half the Sun's circumference and at such a distance, the plane approximation must lead to large errors. However, it is correct to assume that this approximation is sufficiently valid up to distances more than $1/4\ 2\pi\ r_{\odot}$ (i.e., for points situated on the longitude of 90°).

To evaluate r, Reid makes use of the model of interplanetary magnetic field, worked out by Parker [I. 61], by assuming that the solar wind at the earlier stage of the September 28, 1961 flare had a velocity of about 400 km/sec which corresponds to quiet conditions in the interplanetary space. Taking into account the twisting of the field, we get that the ground tube of force starts on the Sun in the region having heliolongitude $\lambda \sim 60^{\circ}$W. The flare had occurred in the region $\lambda \sim 30^{\circ}$E, i.e., the distance along the longitude is of the order of 90°, and therefore, it can be approximately put that $r = 1/4\ 2\pi\ r_{\odot} = 1.1 \times 10^{11}$ cm.

In accordance with diffusion theory, the diffusion coefficient is expressed by the formula $a^2 = v\Lambda/3$ where v is the velocity of particles and Λ is the mean free path in the diffusion medium. Using the data of Bryant et al. [I. 23], Reid obtained the characteristic parameters of diffusion in the corona which are given in Table 15.1 where v is the average velocity of protons in the above-mentioned energy ranges.

Thus, the time variation of solar protons at the earlier stages of the September 28, 1961 flare can be described by a

TABLE 15.1

Characteristic values for the diffusion of accelerated protons in the solar corona [108]

Energy, Mev	$\bar{v}$, cm/sec	$(r/a)^2$, sec	a^2, cm^2/sec	Λ, cm
130-330	1.8×10^{10}	3.2×10^4	3.7×10^{17}	6.4×10^7
330-600	2.2×10^{10}	2.9×10^4	4.1×10^{17}	5.6×10^7

model according to which protons are emitted instantaneously and later on diffuse in solar system with a mean free path of about 600 km by constantly getting into the tubes of forces which extend deep into the solar system.

On the basis of data on September 28, 1961 flare, it is possible to evaluate the upper limit for the coefficient k of losses by taking into account that the term $r^2/4\ a^2t'$ in equation (15.31) defintely predominates over kt' at $1/t' = 0.75$ hrs^{-1}. It follows from this that k must be less than 1.25 hrs^{-1} (3.5×10^{-4} sec^{-1}). This indicates that the protons, on an average, exist in the solar corona at least for one hour before entering the tubes of force of the interplanetary field or they "get lost" in the dense layers of the solar atmosphere.

Let us mention that the value $\Lambda \sim 60$ km has the same order as the dimensions of visible granules on the solar disk which have angular dimension of about 1" corresponding to a linear dimension of about 760 km. It is correct to assume that the magnetic field in chromosphere and near the corona base must have a fine structure with similar characteristic dimensions.

Reid showed that, if k is small (for example, $k \sim 10^{-5}$ sec^{-1}), the arrival of protons from flares on the invisible side of the Sun is highly probable. It was experimentally established that almost all the outbursts of solar particles are associated with flares on the visible side of the Sun. This fact facilitates the assumption that the value of k in most of the cases is much less than 10^{-4} sec^{-1} but it does not eliminate the possibility of occasionaly observing the emission of protons from flares on the invisible side of the Sun. The beam of particles, observed in these cases, must have low intensity but probably large duration.

Reid [108] does not point out a mechanism which could force the protons to move through the solar atmosphere in a disorderly manner. It is important to mention that the effect of collisions on the motion of energetic protons in corona can be neglected. The density of charged particles (mainly protons) near the corona base is approximately equal to 3×10^8 cm^{-3} at the heliocentral distance of about 1.03 $r_\odot$ while the cross section of scattering proton-proton is about 10^{-25} cm^2 at energies of the order of a few hundred Mev. From here, the average mean free path of a proton for scattering will be ~ $3x10^{17}$ cm, i.e., about 10^6 times the circumference of the Sun. Thus, it can be confidently considered that the interactions, responsible for diffusion of protons, must be magnetic in nature.

It is necessary to point out that only the initial stage of a flare of cosmic rays is analyzed in Reid's model. The decrease in the flux of solar particles at a later (isotropic) stage represents evacuation of tubes of force which at the earlier (anisotropic) stage were filled due to diffusion.

The nature of the phase of decrease often abruptly changes with the commencement of geomagnetic storm which is usually observed 1-2 days after a chromospheric flare. These sudden changes can be qualitatively understood on the basis of Reid's model [108]. The sudden commencement of a magnetic storm on the Earth is apparently caused by the arrival of a noncolliding shock wave, in the interplanetary medium, which separates the region of quiet solar wind (before shock wave) from the region of high-velocity solar wind (after shock wave). Since the location of the ground tube of force on the Sun is determined by the curvature of the lines of force, which decreases with an increase in the velocity of solar wind, the propagation of shock wave must be accompanied by a quick displacement of the point, connecting the Earth and the Sun, towards the east. For example, if the velocities of the solar wind before and after the shock wave are respectively equal to 400 and 1500 km/sec, the arrival of shock wave will be accompanied by displacement of the connecting point from a longitude of 60°W to the longitude 15°W with respect to the central meridian. This displacement leads to a change in the value of r in Reids's model and possibly, later on, gives rise to a sudden change in the flux of protons on the Earth! Details of this change, in every case, will be defined by the configuration of the lines of force of the interplanetary field between the shock wave and the cloud of solar plasma which pushes the wave. However, in the long run, an increase in the flux will be observed if the new connecting point lies near the place of flare or there will a decrease in the opposite case. Thus, Reid's model gives a simpler picture of the effect of magnetic storm on propagation of solar particles than the model with protons captured in the trap of the type "magnetic bottle".

At present, much attention is being paid to different models of anisotropic diffusion of solar cosmic rays (see McCracken et al. [109], Axford [110], Burlaga [111], Kondo et al. [112].

16. KINETIC MODEL

As mentioned earlier, the characteristic feature of the interplanetary magnetic field, defining the process of propagation of energetic protons, is the existence of irregularities of dimension 10^{10}-10^{12} cm which is comparable to the radius of curvature of cosmic particles but is small as compared to the dimension of the solar system. The irregularities scatter or reflect the energetic protons forward and backward along the lines of force of the large-scale field which leads to straying of particles in the reference system associated with the irregularities. If $\nu << \omega$, i.e., if the scattering is rare as compared to Larmorov frequency, the particles diffuse weakly in a direction transverse to the lines of force. The motion of particles in-between the acts of scattering is described by the model of the guiding center. On the other hand, if $\nu \sim \omega$, the diffusion transverse to the lines of force is very significant. Obviously, the diffusion coefficient, describing these arbitrary strayings, represents a tensor $\varkappa_{ij}$ while its component parallel to the field is much more than that in the perpendicular direction. In this case, it is necessary to use more rigorous mathematical treatment based on the probable nature of distribution of strayed particles in the interplanetary space.

16.1 Statistical study of anisotropic diffusion. It is clear from the above-mentioned facts that diffusion of solar particles in the interplanetary space, in general, has anisotropic nature. Moreover, their motion in the interplanetary field of configuration, described in Section 13.2, actually consists of two diffusion movements: 1) " one-dimensional diffusion" along an isolated tube of magnetic lines of force of mean free path ℓ_1 which is equal to the average distance, measured along the lines of force, between irregularities of the field and 2) "three-dimensional diffusion" related to chaotic changes in the direction of field in space at the average length ℓ_2 of the quasiregular section. In the case of such a model of motion of solar particles, it is apparently possible to apply probable consideration of the problem as was, for example, done in the work of G.G. Getmantsev [113] the results of which are described below.

The probability of displacement of a particle in the case of one-dimensional duffusion is determined from the expression

$$w_1(x,\ t) = \frac{1}{2\sqrt{\pi\varkappa t}}\, e^{-\frac{x^2}{4\varkappa t}}. \tag{16.1}$$

The coordinate x is measured along the lines of force of the interplanetary field, $\varkappa t = N_1 \ell_1^2/2$ where N_1 is the total number of "collisions" of the particle with the irregularities during a time t. The probability of displacement of a particle in the case of three-dimensional diffusion can be written as

$$w_2(r,\ t) = \frac{1}{2\pi N_2 \left(l_2^2/3\right)^{3/2}}\, e^{-\frac{3r^2}{2N_2 l_2^2}} \tag{16.2}$$

where $N_2 \ell_2 = x$ is the total path covered by the particle along a line of force during time t. The value of x apparently satisfies the inequality $r < x < N_1 \ell_1$. Therefore, the required probability $\omega_3(r, t)$ can be found out by integrating the product $\omega_1 \times \omega_2$ for the interval difined by this inequality. Approximate integration is possible only in two extreme cases. In one of these cases we get the relation

$$w_3 \approx \frac{\sqrt{3}}{2^{3/2}\pi^{3/2}(\varkappa t)^{1/2} r l_2} \exp\left[-\frac{9}{4}\left(\frac{r^4}{3l_2^2 \varkappa t}\right)^{1/3}\right]. \tag{16.3}$$

applicable at $(r^4/\varkappa t \ell_2^2)^{1/6} \gg 1$. In other extreme case $[(r^4/\varkappa t \ell_2^2)^{1/6} \ll 1]$ the corresponding equation for ω_3 has the form

$$w_3 \approx \frac{3}{4\pi^{3/2}(\varkappa t)^{1/2} r l_2}. \tag{16.4}$$

The presence of term r^{-1}, i.e., peculiarity at $r \to 0$, is a characteristic feature of expressions (16.3) and (16.4). In this connection, it should be mentioned that the result, correct in the statistical sense, is possible only at $r/\ell_2 >> 1$. The product ω_3 dr apparently defines the probability of existence of a particle after time t in the spherical layer $4\pi r^2 dr$ with center at the origin where the particle had existed at t = o. As shown by Chandrasekar [41], the diffusion equation represents only a new interpretation of the problem of arbitrary strayings by using the concept of diffusion coefficient $\mathcal{X}$. Therefore, just like expression (14.7) the function ω at a given generation spectrum of solar cosmic rays can be interpreted as the concentration of particles at time t at a distance r from the source.

16.2 Transport equation for solar particles and consideration of the effect of regular interplanetary field. For describing the space-time distribution of solar particles, it is possible to use, in addition to diffusion equation, the method being applied in the theory of transport of neutrons. Such an approach helped V.I. Schishov [50] to estimate the effect of quasiradial interplanetary field on diffusion of solar cosmic rays. Shishov [50] assumed that in the interplanetary space, there existed radial magnetic field of intensity H(r) (r is the distance from the Sun) and magnetic irregularities at which cosmic particles were scattered isotropically. The value of radial magnetic field can be easily characterized by Larmorov frequency $\omega = eH/mc$ as well as by Larmorov radius $\rho = v/\omega$ (it is assumed that $\rho >> a$ --radius of magnetic irregularity). The density of magnetic irregularities in space is characterized by the average time of free run τ while by the term free motion of a particle, we mean the motion under the action of only radial field. For simplicity, it is assumed that τ does not depend on coordinates. The effect of radial field will be significant only at $\omega > 1/\tau$. Since ω decreases on increasing the distance from the Sun, the region of this effect will be limited by some boundary $r = r_b$.

If N relativistic particles of the same velocity v are instantaneously emitted from a point, situated on the Sun's surface, in the radial direction at time t = 0, then as shown in

[50], their concentration $n(r, \theta, t)$ at a point with coordinates r and θ (θ is measured from the direction of primary flight of particles) is described by the equation

$$\frac{\partial(r^2 n)}{\partial t} = \varkappa_r \frac{\partial^2 (r^2 n)}{\partial r^2} + \varkappa_\theta \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} \sin\theta \frac{\partial(r^2 n)}{\partial\theta}, \qquad (16.5)$$

$$\varkappa_r = \frac{v\Lambda}{3}, \quad \varkappa_\theta = \frac{2\rho^2}{3r^2\tau},$$

where $\Lambda \leqslant v\tau$ is the average path covered by the particle without colliding with irregularities.

The essence of the approximations made while deriving the equation (16.5) lies in the fact that the derivative $\partial^2 n/\partial t^2$ is considered to be small as compared to $1/\tau(\partial n/\partial t)$. Equation (16.5) is valid only at $r < r_b$. At $r > r_b$, it is necessary to make use of the usual diffusion equation

$$\frac{\partial n}{\partial t} = \frac{\varkappa_r}{r}\left(\frac{\partial}{\partial r} r^2 \frac{\partial n}{\partial r} + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial n}{\partial\theta}\right). \qquad (16.6)$$

The value of r_b is determined in the following way: $\varkappa_\theta(r_b) = \varkappa_r/r_b^2$. It is necessary to add the following conditions to equations (16.5) and (16.6)

$$\int n\,dV = N; \quad n(r, \theta, 0) = \frac{1}{4\pi\Lambda}\delta\left(\frac{r - r_\odot}{\Lambda}\right)\delta(1 - \cos\theta)\frac{1}{r^2}, \qquad (16.7)$$

in addition to the condition of continuity of transition of one solution into the other at $r = r_b$ (i.e., equality of concentrations and fluxes on transitting through r_b).

If it is considered that $\varkappa_\theta$ = const, i.e., if some effective value $\bar{\varkappa}_\theta$ is taken and if the dependence of $\varkappa_r/r^2$ on r is neglected at the values of r close to r_b, the variables r and θ can be separated:

$$n(r, \theta, t) = \Psi(\theta, t)\, T(r, t), \qquad (16.8)$$

where $\Psi(\theta, t)$ at $1/4\bar{\varkappa}_\theta > t$ and $\theta \leqslant 1$ has the form

$$\Psi = \frac{1}{\bar{\varkappa}_\theta t}\exp\left(-\frac{\theta^2}{4\bar{\varkappa}_\theta t}\right). \qquad (16.9)$$

At large values of t, Ψ can be expandded into Legendre's polynomial

$$\Psi=\sum_{k=1}^{\infty}(2k+1)P_k(\cos\theta)\exp\left[-k(k+1)\bar{\varkappa}_\theta t\right], \qquad (16.10)$$

and only the first few terms can be used. It is obvious from (16.10) that $\Psi\to 1$ at $t\to\infty$. The parameter $T(r,t)$ at $r > r_b$ and $t > (1.3\ r_b)^2/6\ \varkappa_r$ has the form

$$T=\frac{N}{(4\pi\varkappa_r t)^{3/2}}\exp\left[-\frac{(r-r_\odot)^2}{4\varkappa_r t}\right]. \qquad (16.11)$$

Therefore, the following relation is valid within certain limits:

$$n=\frac{N}{(4\pi\varkappa_r t)^{5/2}}\exp\left[-\frac{(r-r_\odot)^2}{4\varkappa_r t}-\frac{\theta^2}{4\bar{\varkappa}_\theta t}\right] \qquad (16.12)$$

It should be mentioned that equation (16.5) describes the process of diffusion satisfactorily only at large values of t. As it follows from the equation (16.12), the concentration of particles at a point with coordinates r and θ becomes maximum at

$$t_{\max}=\frac{1}{10}\left[\frac{(r-r_\odot)^2}{\varkappa_r}+\frac{\theta^2}{\bar{\varkappa}_\theta}\right]. \qquad (16.13)$$

If the lines of force are not directed radially but are twisted and if their curvature can be neglected at a distance of the order of mean free path; equation (16.5) is applicable only if r is taken as the length of path along the line of force and θ as the angle between the direction of exit of the line of force from the Sun and the zero direction. In the beginning, the particles will propagate in some curved cone which will widen with the passage of time. When the cone widens so much that the region covered gets twisted slightly, then the diffusion gets radial in nature. If the angle between the initial direction of flight of particles and the radius, passing through the point of intersection of the cone axis with the surface $r = r_b$, is denoted by θ_0, it is necessary to write $|\theta \pm \theta_0|$ in equations (16.9) and (16.10) in place of θ (plus sign for the eastern side and minus for the western side).

Observations show that particles from the western limb of the Sun reach the Earth most quickly. Best conformity between the calculated curve (16.13) and observational data

(Fig. 16.1), taken from the work of Ellison et al. [V.2], was obtained at $\theta_o = 75^{\circ}$ and $1/\varkappa_{\theta} = 300$ min where $\varkappa_{\theta} \approx \varkappa_{\theta}/r_b$ at $H \sim r^{-2}$. Putting $r^2_{\oplus}/\varkappa r \approx 200$ min ($\varkappa_r \approx 2 \times 10^{22}$ cm^2/sec) for relativistic particles, we get $r_b = 0.8\, r_{\oplus}$ and $H(r_{\oplus}) = H_o = 10^{-5}$ gauss. From this, it follows that formula (16.13) is applicable at 30 min $< t <$ 80 min.

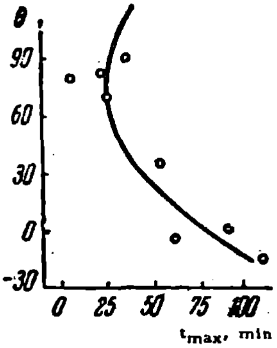

Fig. 16.1. Dependence of the time of appearance of maximum intensity of solar particles on the position of chromospheric flare. The continuous curve is calculated from the equation (16.13).

The concentration of flares on the western limb should apparently fall more steeply as compared to the spherically symmetrical case. It was actually observed by A. A. Stepanyan [100] for the May 4, 1960 flare in the energy range of 1-2 Gev (Fig. 16.2). On comparing the observational data of Sulfur station with the curve calculated by considering the radial field [50], the values $\Lambda = 5 \times 10^{12}$ cm and $H_o = 10^{-6}$ gauss were obtained. According to the data of A.N. Charakhch'yan et al. [53], this effect was not observed in the region of low energies and therefore, $H_o < 5 \times 10^{-6}$ gauss at $\Lambda = 1.3 \times 10^{12}$ cm.

On the other hand, flares on the western limb must give a wide diffused maximum which was actually observed for the September 3, 1960 flare (Fig. 16.3). Satisfactory conformity with the observations was obtained by Shishov [50] at $\Lambda = 1.3 \times 10^{12}$cm and $H_o = 10^{-6}$ gauss and therefore, there is no necessity of assuming prolonged emission of protons from the flare region on the Sun as was done in [63].

It is however necessary to point out that the value of H_o, obtained for different flares, is slightly low since in the

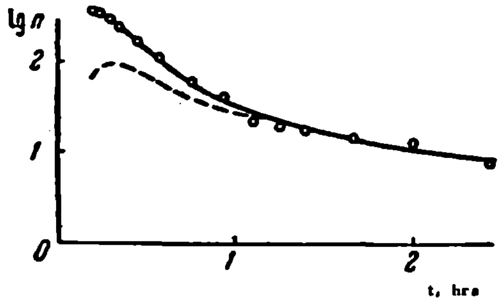

Fig. 16.2. Time variation of solar particles for a flare on the western limb of the Sun: continuous curve-diffusion on considering the radial field; dotted curve - spherically symmetrical diffusion and circles-data of Sulfur station for the May 4, 1960 flare.

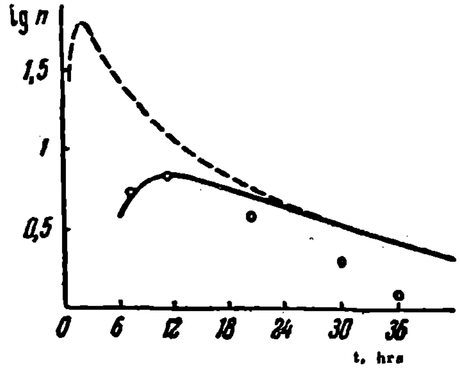

Fig. 16. 3. Time variation of solar particles for a flare on the eastern limb of the Sun: continuous curve - diffusion on considering the radial field; dotted curve - spherically symmetrical diffusion and circles - data [63] for the September 3, 1960 flare.

work of V. I. Shishov [50], it was assumed that $\tau \approx$ const while , in reality, $\tau \sim r$. If one considers the dependence of τ on r it leads to an increase in the value of H_0 by 2-5 times. The assumption of the dependence $\tau(r)$ has a weak effect on the equation (16.13) and therefore, the value of 10^{-5} gauss can be considered to be more correct.

Therefore, on an average, $H_0 = 5 \times 10^{-6}$ gauss near the Earth's orbit. Rocket observations give the value of the intensity of field higher by about one order. This difference can be explained by the fact that the intensity of the field at the ecliptic plane is more than that averaged for a sphere.

A method is given in another work of V.I. Shishvo [114] for determining the value of regular component of the interplanetary magnetic field near the Earth's orbit from a study of the effect of drift on the direction of maximum flux of particles coming from the Sun. Here, use is made of the fact that high-energy solar protons are practically led by the lines of force of the regular magnetic field [4]. It is also known during the initial stage of some flares (for example, May 4, 1960 flare [4]), the width of the angular spectrum of particles, reaching the Earth, is very small and therefore, they can be considered to be practically flying along the lines of force of the regular field. If the small effects of scattering at the irregularities of the field are neglected, the propagation of particles corresponds to the equation of motion in the drift approximation [115].

$$\mathbf{v}=v_{\parallel}\boldsymbol{\tau}-\frac{1}{\omega}\left(v_{\parallel}^{2}\frac{\mathbf{n}}{\tilde{r}}+\frac{v_{\perp}^{2}}{2\omega}\nabla\omega\right). \qquad (16.14)$$

where $\mathbf{v}$ -the average rate of motion of guiding center of the particle;

τ -the unit vector along the line of force of the magnetic field;

$\mathbf{n}$ -the unit vector of normal to the line of force;

$\tilde{r}$ -the radius of curvature of the line of force;

ω -the Larmorov frequency;

$v_{\parallel}$ -the component of the velocity of particle along the line of force;

$v_{\perp}$ -the component of the velocity of particle perpendicular to the line of force.

Since the particles mainly move along the lines of force ($v_{\perp} << v_{\parallel}$), it can approximately be written that

$$\mathbf{v}=v_{\parallel}\boldsymbol{\tau}-\frac{v_{\parallel}^{2}}{\omega\tilde{r}}\mathbf{n}. \qquad (16.15)$$

The direction of vector **v** is actually the direction of the axis of symmetry of the beam of particles reaching the Earth .

Angle $\Delta\theta$, by which the direction of the axis of symmetry of the beam is deviated from the direction of the line of force due to drift, is determined from the following approximate relation:

$$\Delta\theta = \frac{v_\parallel}{\omega\tilde{r}}. \tag{16.16}$$

If r is the distance from the Sun, Ω is the angular velocity of rotation of the Sun and if u is the velocity of the solar wind, the lines of force of the regular magnetic field will make an angle φ with the radial direction; φ and $\tilde{r}$ in this case are determined from the relations

$$\operatorname{tg}\varphi = \frac{\Omega r}{u}, \tag{16.17}$$

$$\frac{1}{\tilde{r}} = \frac{\sin\varphi}{r}\,\frac{2+\operatorname{tg}^2\varphi}{1+\operatorname{tg}^2\varphi}. \tag{16.18}$$

Formulas (16.17) and (16.18) are valid only near the ecliptic plane. If $\Delta\theta$ is known, it is possible to find out ω and intensity of the magnetic field from relations (16.16)-(16.18). The angle $\Delta\theta$ can be determined by comparing the directions of the axis of symmetry of beams of particles having different energies since $\Delta\theta \sim 1/\omega \sim \mathcal{E}$.

For the May 4, 1960 flare, the direction of axis of symmetry of the beam of particles with $\mathcal{E} = 3\times10^9$ ev (neutron component) coincided with the direction of the axis of symmetry of particles with $\mathcal{E} = 10^{10}$ ev (meson component) with an accuracy of 5°[4]. From this , we get $\Delta\theta \lesssim 0.1$ radian for particles with $\mathcal{E} = 10^{10}$ ev. If $\varphi \approx 50^\circ$ [4], then from equation (16.18) we get $r \approx 1.5\times10^{13}$ cm. Similarly, putting $v_\parallel = 3\times10^{10}$ cm/sec, we get $\omega \gtrsim 2\times10^{-2}$ sec^{-1}. From this, $B \gtrsim 2\times10^{-5}$ gauss. Since drift schedule is established during a period of the order of $1/\omega$, the obtained estimate refers to the region near the Earth and is the average for the interval approximately equal to Larmorov radius of 10^{12} cm.

16.3 Kinetic equation in Fokker-Planck approximation. As is shown, some flares show strong anisotropy in angular distribution of high-energy solar protons at the initial stage of the flare. It means that protons reaching the Earth during this period do not undergo significant deviations. Duffusion approximation is not valid in this case and it is necessary to use more general equations.

Measurements on interplanetary magnetic field with the help of "Mariner-2" [20] show that near the Earth's orbit, there exists an irregular magnetic field with mean square intensity $H = 3 \times 10^{-5}$ gauss and dimension of irregularities $\lesssim 10^{11}$ cm. Relativistic proton $\mathcal{E} = 3 \times 10^9$ ev scatters at such an irregularity through an angle $< 20^\circ$. Therefore, it is possible to use the kinetic equation in Fokker-Planck approximation for describing the propagation of high-energy protons in the interplanetary medium.

The work of V.I. Shishov [116] is devoted to the solution of Fokker-Planck equation applicable to a solar flare and main attention has been paid to the explanation of conditions under which it is possible to observe strong anisotropy in the angular distribution of solar protons.

Basic equation. We will assume that the interplanetary magnetic field consists of two components:

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1, \tag{16.19}$$

where $\mathbf{B}_0$ is the regular magnetic field (it approximates the large-scale fields whose dimensions are much more than the Larmorov radius of a particle) and B_1 is the uniform casual field with can be described by the expressions

$$\langle \mathbf{B}_1 \rangle = 0, \quad \langle \mathbf{B}_{1l}(r_1)\,\mathbf{B}_{1l}(\mathbf{r}_2) \rangle = \overline{B_1^2}\, e^{-\frac{|\mathbf{r}_1 - \mathbf{r}_2|}{a^2}} \tag{16.20}$$

where a is the characteristic radius of the irregularity, $\overline{B^2}_1$ is the mean square intensity of the arbitrary field and B_{1r}, $B_{1\eta}$ and $B_{1\xi}$ are the three-dimensional components of the vector in the spherical system of coordinates $i = r, \eta, \xi$. The angular brackets indicate the average for the three-dimensions. The magnetic field is considered to be stable.

Let us denote the unit vector in the direction of motion of particle by $\mathbf{k}$ ($\mathbf{k} = \mathbf{v}/|\mathbf{v}|$). For the change $\Delta \mathbf{k}$ in vector $\mathbf{k}$ during the interval Δt, we have

$$\Delta \mathbf{k} = \frac{e}{mc} \int_0^{\Delta t} [\mathbf{k}' \times \mathbf{B}']\, dt \approx \frac{e}{mc} \left[\mathbf{k} \times \int_0^{\Delta t} \mathbf{B}'\, dt' \right], \qquad (16.21)$$

where m is the total mass of the particle while Δt is selected in such a manner that the particle can pass through a sufficiently large number of irregularities and at the same time, its deviation from the initial direction is small. With the help of equations (16.20) and (16.21), we obtain

$$\left.\begin{aligned}
\langle \Delta k_\varphi \rangle &= \frac{eB_0}{mc}\Delta t = \omega \Delta t, \\
\langle \Delta k_\theta \rangle &= \frac{e^2 \overline{B_1^2}}{m^2c^2}\,\frac{2\sqrt{\pi}a}{v} \operatorname{ctg}\theta \cdot \Delta t = q \operatorname{ctg}\theta \cdot \Delta t, \\
\langle (\Delta k_\theta)^2 \rangle &= 2q\,\Delta t, \\
\langle (k_\varphi)^2 \rangle &= \frac{2q}{\sin^2\theta}\Delta t,
\end{aligned}\right\} \qquad (16.22)$$

where θ and φ are the angular coordinates; θ is measured from the radius and φ is the azimuth angle. The parameter $q = 2\, B_1{}^2 a e^2 \sqrt{\pi}/mc^2 v$ [sec^{-1}] represents the diffusion coefficient in the angular space.

Using these expressions and basing upon Markov's equation, relating the values of distribution function $N(r, \theta, \varphi, t)$ at t and $t + \Delta t$, we get the kinetic equation in Fokker-Planck approximation:

$$\frac{\partial N}{\partial t} + v\mathbf{k}\operatorname{grad} N - \frac{v \sin\theta}{r}\frac{\partial N}{\partial \theta} - \frac{v \sin\theta \sin\varphi}{r} \operatorname{ctg}\eta \frac{\partial N}{\partial \varphi} =$$
$$= \frac{q}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial N}{\partial\theta} + \frac{q}{\sin^2\theta}\frac{\partial^2 N}{\partial\varphi^2} + \omega\frac{\partial N}{\partial\varphi}, \qquad (16.23)$$

where $N(r, \theta, \varphi, t)\,dr\,dk$ is the number of particles in volume dr and with velocities directed in solid angle dk.

The energy of a particle does not change during scattering at irregularities since the field is considered to be stable. A similar derivation of equation (16.23) can be found in the work of Chandrasekar [41].

Spherically symmetrical flare. Let us first of all consider a point spherically-symmetrical flare in an infinite homogeneous medium. The kinetic equation and the initial condition in this case will be

$$\frac{\partial N}{\partial t} + v\cos\theta\frac{\partial N}{\partial r} - v\frac{\sin\theta}{r}\frac{\partial N}{\partial \theta} = q\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial N}{\partial\theta}, \quad (16.24)$$

$$N|_{t=0} = \frac{\bar{N}}{16\pi^2 r^2}\delta(r). \quad (16.25)$$

Moreover, $N(r, \theta, t)$ must be a periodic and symmetrical function of θ :

$$N(\theta) = N(\theta + 2\pi), \quad N(\theta) = N(-\theta). \quad (16.26)$$

Expanding N into Legendre polynomial !

$$N = \sum_{k=0}^{\infty} a_k(r, t) P_k(\cos\theta), \quad (16.27)$$

we get a chain of equations for the coefficients a_k from which expressions for a_0 and a_1 have been obtained in [116] (it should be mentioned that $4a_0$ is the concentration and $va_1/3$ is the flux of particles). Graphs of the dependence of a_0 and a_1 on r at qt = 3 are given in Fig. 16.4. (continuous curves). The

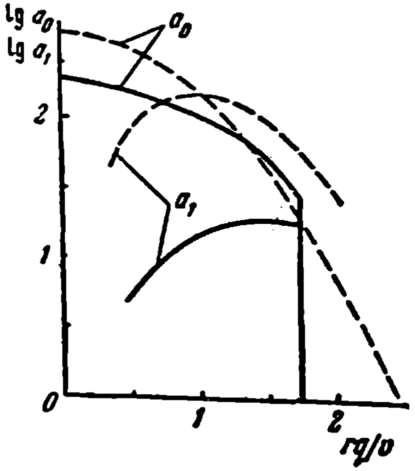

Fig. 16.4. Dependence of concentration of particles on distance in kinetic (continuous curves) and diffusion (dotted curves) approximations.

values of a_0 and a_1 in the diffusion approximation are given in the same Fig. (dotted curves) for comparison. It is obvious that the main difference lies not in the shape of curve but in the fluxes.

While determining a_0 and a_1, the terms containing a_2 were neglected by assuming that $a_2 \ll a_0$, a_1. This condition is satisfied right up to $r = vt\sqrt{3}$ at $qt \lesssim 5$. At large values of t, these expressions for a_0 and a_1 are applicable only at $r < r_0 < vt/\sqrt{3}$ and this equality becomes more significant on increasing t. At $vt < r < vt/\sqrt{3}$, the distribution of particles is described by δ-function since a_0 has not been taken into consideration. Thus, in order to describe particles existing in the zone $r > r_0$, it is necessary to take into account a_2, a_3, etc., i.e., particles are distributed anisotropically in this zone.

Let us come back to the problem of angular distribution of particles in the zone $r > r_0$. For solving this problem, derivatives with respect to θ in the equation (16.24) are replaced by finite differences by direct methods. As a result of this, we get a system of equations with partial derivatives of first order in place of equation (16.24):

$$\frac{\partial N_i}{\partial t} + v\cos\theta_i \frac{\partial N_i}{\partial r} - \frac{v\sin\theta_i}{2rh}(N_{i+1} - N_{i-1}) =$$

$$= \frac{1}{h^2}(N_{i+1} - 2N_i + N_{i-1}) + \frac{1}{2h}\operatorname{ctg}\theta_i (N_{i+1} - N_{i-1}). \quad (16.28)$$

Here h is the step and $N_i = N(r, \theta_i, t)$ is the value of function $N(r, \theta, t)$ averaged for the interval $\theta_i - \frac{1}{2h}$ and $\theta_i + \frac{1}{2h}$, ($i = 1, 2, 3 \ldots\ldots$). Since the particles are distributed anisotropically in the zone $r > r_0$, the terms containing N_2 can be neglected in equation (16.28). Considering that the thickness of this zone is less than the distance from the center at not very large values of t, sphericity can also be neglected. The solutions for N_0 and N_1, obtained in [116] satisfactorily describe the propagation of particles at $qt < 1$ when their velocities are mainly directed forward. At large values of t, these solutions are applicable only to the outermost parts of the zone $r > r_0$. For the inner parts of this zone, it is necessary to consider those particles which enter the zone $r < r_0$ and again come into the zone $r > r_0$ after multiple scattering. Results of numerical calculations of the time dependence of the intensity of particles for directions 20, 60, 100 and 180° at distances rq/v = 1, 3, and 5 [116] show that strong anisotropy in the angular distribution of particles for a spherically symmetrical flare is observed only at rq/v $\lesssim$ 1 at the time of maximum concentration (i.e., N_0 and N_1 differ significantly).

Axisymmetrical flare. Let us assume that the particles are emitted at the point r = 0 along the axis η = 0. The kinetic equation in this case has the following form:

$$\frac{\partial N}{\partial t}+v\cos\theta\frac{\partial N}{\partial r}-v\frac{\sin\theta}{r}\frac{\partial N}{\partial\theta}+$$
$$+v\frac{\sin\theta\cos\varphi}{r}\frac{\partial N}{\partial\eta}-v\frac{\sin\theta\sin\varphi}{r}\operatorname{ctg}\eta\frac{\partial N}{\partial\varphi}=$$
$$=\frac{q}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial N}{\partial\theta}+\frac{q}{\sin^2\theta}\frac{\partial^2 N}{\partial\varphi^2}+\omega\frac{\partial N}{\partial\varphi}. \qquad (16.29)$$

Putting N in the form of a series:

$$N=b_0(r,\ \eta,\ \theta,\ t)+\sum_{k=1}^{\infty}[b_k(r,\ \eta,\ \theta,\ t)\cos k\varphi+c_k(r,\ \eta,\ \theta,\ t)\sin k\varphi], \qquad (16.30)$$

for propagation along the coordinate η, we get the following equation defining b_0 in the diffusion approximation:

$$\frac{\partial b_0}{\partial t}+v\cos\theta\frac{\partial b_0}{\partial r}-\frac{v\sin\theta}{r}\frac{\partial b_0}{\partial\theta}=$$
$$=\frac{qv^2\sin^4\theta}{4r^2(\omega^2\sin^4\theta+q^2)}\frac{1}{\sin\eta}\frac{\partial}{\partial\eta}\sin\eta\frac{\partial b_0}{\partial\eta}+\frac{q}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial b_0}{\partial\theta}. \qquad (16.31)$$

Following initial condition :

$$b_0|_{t=0}=\frac{\bar{N}}{16\pi^2r^2}=\delta(r)\delta(1-\cos\eta)\delta(1-\cos\theta), \qquad (16.32)$$

as well as the condition of periodicity of η and θ should be imposed on the equation (16.31).

If $\omega \gg q$, it is seen from the equation (16.31) that the coefficient, on taking derivative with respect to η, does not depend on θ If it also does not depend on r, we get

$$b_0 = N_{sp}\frac{1}{2\bar{\varkappa}_\eta t}\exp\left(-\frac{\eta^2}{4\bar{\varkappa}_\eta t}\right). \qquad (16.33)$$

Here N_{sp} is the solution of a spherically-symmetrical flare and $\bar{\varkappa}_\eta = qv^2/4r^2\omega^2$ is the effective value of the coefficient in the case of derivative with respect to η.

Let us now consider the effect of nonsphericity of a flare on the conditions for observing strong anisotropy. As shown in [116], the intensity in the case of a spherically symmetrical flare grows very quickly and the term $1/\bar{\varkappa}_\eta t$ does not play a significant role in the anisotropic section of the curve The exponential term exp $(-\eta^2/4\bar{\varkappa}_\eta t)$ can displace the maximum into the isotropic region at $\eta^2 > 4\varkappa_\eta t$. Thus, a strong anisotropy will be observed only in the cone $rq/v \lesssim 1$, $\eta^2 < 4\bar{\varkappa}_\eta t$.

Comparison with observations. The conclusion drawn here can be compared with the observational data [4] on the May 4, 1960 flare. The direction of the axis of symmetry of the beam of arriving protons got deviated form the direction on the Sun by 50° towards the west. The particles were apparently led by the lines of force of the regular spiral-type field and therefore, the angle in this case should be measured not from the the radial direction but from the direction of line of force at the given point which coincided with the axis of symmetry of the beam. Taking this into account, let us apply the results, obtained for the radial field, to the real field by considering that the other changes are insignificant.

According to data [4], strong anisotropy was retained for half an hour after attaining the maximum density of particles. It firstly means that the Earth during this flare was situated in the favorable cone. Secondly, the duration of strong anisotropy was defined by the duration of functioning of the source since, as shown in [116], duration of strong anisotropy is not more than a few minutes in the case of an instantaneous source. The values of the intensity in the directions $\theta = 40°$ and $\theta = 60°$ are shown in Fig. 16.5 as a function of t at $q = 2\times10^{-3}$ sec^{-1}, $r = 1.5\times10^{13}$ cm, and $\eta = 0$. Function of the power of source was of the form $\sim \exp(-t/T_0)$ where $T_0 = 16$ min. Values of the flux observed at corresponding points on the Earth are marked by circles and triangles. It may be seen that these curves satisfactorily describe the amplitude and duration of anisotropy.

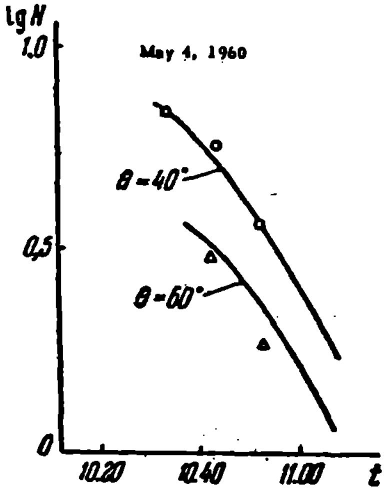

Fig. 16.5. Dependence of the intensity of solar particles on time for the May 4, 1960 flare in the directions θ = 40° and θ = 60° with respect to the axis of symmetry of the beam.

The parameter T_0 can be the duration of function of the source as well as the duration of scintillation of duffusion region in the Sun's surroundings. Let us consider the second version. The duration of a scintillation of a sphere of radius r, filled with a medium of diffusion coefficient $\varkappa_r$, is approximately equal to $r^2/\varkappa_r$. Putting $r = 10\ r_\odot = 7 \times 10^{11}$ cm and assuming the scintillation time to be equal to 16 minutes, we get $\varkappa_r = 5 \times 10^{20}$ cm^2/sec. Of course, it is not necessary to consider that the diffusion region surrounding the Sun is sharply isolated. The assumption about a gradual change in duffusion coefficient on changing the distance from the Sun is more probable (see Section 14.6). In this case, $\varkappa_r$ is some effective value of diffusion coefficient at small distances from the Sun while $\varkappa_\delta$ is its mean value at large distances, right up to the Earth's orbit (since anisotropic phase of flare was studied, the medium existing at the Earth's orbit practically did not affect the value of the parameters being determined).

The diffusion coefficient, measured from the falling section of the curve, mainly refers to space beyond the Earth's orbit. According to the data obtained by A.N. Charakhch'yan et al. [63], it was equal to 3×10^{22} cm^2/sec for the May 4, 1960 flare. From this, V.I. Shishov concludes that the diffusion coefficient at $r < 1$ a.u. significantly increases with distance (approximately as r^2) while $\varkappa \approx$ const at $r > 1$ a.u. It can be explained by the effect of regular field which is extremely azimuthal beyond the Earth's orbit.

16.4 Determination of characteristics of the interplanetary magnetic field from anisotropic stage of a flare. As shown in Section 16.3, it is possible to make use of kinetic equation in Fokker-Planck approximation for analyzing the anisotropic stage of a flare of cosmic rays with $\mathcal{E}_k \gtrsim 10^9$ ev. On the basis of this approximation, V.I. Shishov [117] evaluated the characteristics of the interplanetary magnetic field from the anisotropic stage of cosmic-ray flares of May 4, 12 and November 15, 1960.

It was assumed in [117] that relativistic solar protons with $\mathcal{E}_k \gtrsim 10^9$ ev undergo small-angle scattering on account of magnetic irregularities. This assumption was mainly based on the data of magnetic measurements of "Mariner-2". Given below are the additional points in favor of the hypothesis of small-angle scattering on the basis of the data of McCracken [4] for the above-mentioned three flares.

1) Proton beams from the above-mentioned three flares had an axis of symmetry directed at an angle of about 50° towards the west with respect to the Earth-Sun line. Morevoer, the difference in these directions was not more than 20° for various flares. Had the magnetic irregularities deflected protons with $\mathcal{E}_k > 10^9$ ev by an angle $> 20°$ and had the distance between them been comparable to their dimensions (porosity of the order of unity), the difference in the directions of the axes of symmetry would have corresponded to the scattering angle in the case of collision of a proton with one irregularity. In particular, if the dimension of irregularities is more than the Larmorov radius of a particle, the axis of symmetry can have every direction with the same probability.

2) The average angular distribution establishes only after a sufficiently large number of scatterings and therefore,

in the case of large scattering angles, the intensity, which is a function of direction and time, must undergo significant fluctuations (with respect to time and direction) practically during the whole of the anisotropic stage. Since the observations show that the intensity is a gradual function, it can be assumed that, if the the irregularities are situated densly, they scatter the particles through small angles.

3) If the irregularities have large porosity, the kinetic equation can be applied to both the cases. Here, it should be kept in view that the term, describing collisions in the case of large-angle scattering , represents the integral which in the case of small-angle scattering can be approximately replaced by the second derivative with respect to direction. It is clear that, in the first case, the angular spectrum should be much more plane than in the second case since the particle in the first case attains an arbitrary direction after scattering with sufficiently great probability while in the second case, the particle changes its direction only due to diffusion in the angular space. Nature of the angular spectrum during the May 4, 1960 flare cannot be explained by large-angle scattering . This conclusion seems to be also generally valid for the November 15, 1960 flare.

It is assumed in the work of V. I. Shishov [117] that the regular magnetic field is caused by the outflow of plasma from the Sun which rotates with an angular velocity Ω . The plasma moves at a constant velocity u. The irregular field is characterized by the rate of change of the mean square angular deviation q [see (16.22)]. The characteristic time of free run, in this case, with respect to rotation through an angle $\approx \pi/2$ will be $\tau = 1/2q$ while the characteristic mean free path $\Lambda = v\tau = v/2q$. It follows from this that $\varkappa = v^2/6q$ and $q \sim v^{-2} \sim \varepsilon^{-2}$.

Let us assume that the regular field is sufficiently strong and therefore, drift can be neglected. In this case, the motion of particles across the lines of force of the irregular field is due to their diffusion and it is much slower than the motion of particles along the lines of force of the regular field. To the first approximation, the terms describing the motion of particles across the lines of force of the regular field can be neglected in the kinetic equation. It is permissible only in the presence of sufficiently strong anisotropy. Under these assumptions, the kinetic equation near the ecliptic plane will be

$$\frac{\partial N}{\partial t}+v\cos\theta\frac{\partial N}{\partial l}-\frac{v\sin\theta}{2r}\left[1+\frac{1}{(1+b^2r^2)^{3/2}}\right]\frac{\partial N}{\partial\theta}=q\,\frac{1}{\sin\theta}\,\frac{\partial}{\partial\theta}\sin\theta\frac{\partial N}{\partial\theta}. \tag{16.34}$$

Here N – the distribution function;

θ -the polar angle measured from the direction of the line of force of the regular field at the given point;

ℓ -the path along the line of force;

$b = \frac{u}{\Omega}$ – a parameter characterizing the curvature of the line of force.

Solving the equation (16.34) by the method of straight lines, i.e., replacing derivatives with respect to θ by finite differences, in place of equation (16.34) we get a system of linear differential equations with partial derivatives of the first order for the functions $N_i\,(\ell, t) = N\,(\theta_i, \ell, t)$.

Let us, first of all, consider the case of two point approximation ($\theta_1 = 45°$, $\theta_2 = 135°$). In this case, $N_1 = N(\ell, \theta = 45°, t)$ and $N_2 = N(\ell, \theta = 135°, t)$ represent the intensities averaged for the intervals [0°, 90°], [90°, 180°]. For N_1 and N_2, we have the system

$$\left.\begin{aligned}&\frac{\partial N_1}{\partial t}+0{,}71v\frac{\partial N_1}{\partial l}=(0{,}72q+a)(N_2-N_1),\\&\frac{\partial N_2}{\partial t}-0{,}71v\frac{\partial N_2}{\partial l}=(0{,}72q-a)(N_2-N_1),\\&a=\frac{0{,}23v}{2r}\left[1+\frac{1}{(1+b^2r^2)^{3/2}}\right].\end{aligned}\right\} \tag{16.35}$$

For the anisotropic stage of flares, N_2 in the first equation of the system (16.35) can be neglected as compared to N_1. Therefore, we get the following solution :

$$\left.\begin{aligned} N_1(l,\ t) &= N_1\left(l_0,\ t-\frac{l-l_0}{0{,}71v}\right)\exp\left[-(0{,}72q+a)\frac{l-l_0}{0{,}71v}\right], \\ N_2(l,\ t) &= \int\limits_0^t N_1(l_0,\ t-2\tau)\exp\left[-1{,}44q\tau\right](0{,}72q-a)\,d\tau. \end{aligned}\right\} \quad (16.36)$$

It follows from (16.36) that the value of q, averaged for the interval [l_0, l_0 + 0.71 v/1.44 q], can be obtained by observing N_1 and N_2 on the Earth. Equation (16.36) can be used only at the initial stage of a flare (approximately before N_2 becomes maximum) when it can be assumed that the particles, flying backward, experience only one effective collision.

In the case of three-point approximation (θ_1 = 30°, θ_2 = 90°, θ_3 = 120°), we have the following system for N_1, N_2 and N_3 :

$$\left.\begin{aligned} &\frac{\partial N_1}{\partial t}+0{,}87v\frac{\partial N_1}{\partial l}=(1{,}79q+a)(N_2-N_1), \\ &\frac{\partial N_2}{\partial t}=(0{,}96q-2a)N_1-1{,}92qN_2+(0{,}96q+2a)N_3, \\ &\frac{\partial N_3}{\partial t}-0{,}87v\frac{\partial N_3}{\partial l}=(1{,}79q-a)(N_2-N_3). \end{aligned}\right\} \quad (16.37)$$

Considering N_1 and N_3 to be known and solving the second equation of the system (16.37), we get

$$\begin{aligned} N_2(l_0,\ t) = \int\limits_0^t &[N_1(l_0,\ t-\tau)(0{,}96q-2a)+ \\ &+N_3(l_0,\ t-\tau)(0{,}96q+2a)]\exp(-1{,}92q\tau)\,d\tau. \end{aligned}$$

Thus, the value of the parameter q can be obtained by comparing N_2 with N_1 and N_3. Since, however, the accuracy of determination of q is not high at N_1 comparable to N_3 (in the case of weak anisotropy), it is advisable to use only the anisotropic region. We finally get

$$N_2(l_0,\ t)=\int\limits_0^t N_1(l_0,\ t-\tau)\exp(-1{,}92q\tau)(0{,}96q-2a)\,d\tau. \quad (16.38)$$

The value of parameter q, determined from equation (16.38), is the average value for the interval [$l_0 - \frac{0.3v}{2q}$, l_0]

This interval exists in the Earth's orbit since N_2 is defined by the value of N_1, i.e., by the flux of particles coming from the Sun.

Similar expressions can be obtained in approximations with large number of points characterizing the angular spectrum. Obviously, the larger the number of details that can be differentiated in the spectrum of angular distribution of particles from a flare, the higher will be the accuracy of determination of q as a function of distance. Let us now analyze the observational data.

May 4, 1960 flare. This flare was characterized by strong anisotropy and by absence of significant fluctuations. It points out that relativistic protons during collision with irregularities were deflected through an angle of the order of a few degrees or less. In the case of two-point approximation, N_1 and N_2 cannot be compared since N_2 was not observed for this flare. It can, however, be assumed that the maximum in N_2 appeared not earlier than 1.5 hours after the appearance of maximum in N_1. As seen from the equation (16.36), this delay is approximately equal to 1.5/q. From this, we get the value $q = 2 \times 10^{-4}$ sec^{-1} for the range from 1 a.u. to a few a.u.

By comparing N_1 and N_2 in the case of three-point approximation, we get $q = 1.5 \times 10^{-3}$ sec^{-1}. Here, it was assumed that $b(r_*) = 1$. This value of q refers to the range from 0.67 a.u. to 1 a.u. It can approximately be taken equal to 0.8 a.u. By comparing intensities in the directions 70°, 90° and 110°, it was found that $q = 5 \times 10^{-4}$ sec^{-1}. This value refers to $r = 1$ a.u.

November 12, 1960 flare. This flare was characterized by extremely prolonged stage of outburst as well as by the presence of two maxima. Only the first outburst was anisotropic. By comparing N_1 and N_2 on the basis of formula (16.36), we get $q = 5 \times 10^{-4}$ sec^{-1}. This value approximately refers to a distance of 1.5 a.u. from the Sun. It was not possible to get more specific information on this flare due to low anisotropy.

If it is assumed that the second outburst was associated with capture of the Earth by the corpuscular beam, it is possible to determine the value of diffusion coefficient from the relation between the flux F and concentration gradient : $F = \varkappa\ (\partial n / \partial r)$. Considering that the outburst is mainly defined by the arrival of the corpuscular beam, we get $\partial n / \partial r = 1/u \cdot \partial n / \partial t$ where u is the velocity of plasma. Since significant flux was not observed, it can be assumed that $F < 0.1\ n\ u$. Using the observational data, we get $\varkappa < 4 \times 10^{20}\ cm^2/sec$. The duration of scintillation of a region of dimension r, filled with a medium of diffusion coefficient $\varkappa$, is equal to $r^2/\varkappa$. After the second outburst, the characteristic time of attenuation was of the order of 2 hours. The dimension of the region at $\varkappa = 10^{20}\ cm^2/sec$ should not be more than 1.5×10^{12} cm. It means that only the forefront of the beam is densely formed while the regions following it are filled with much weaker field.

November 15, 1960 flare. By comparing N_1 and N_2 on the basis of formula (16.36), we get $q = 4 \times 10^{-4}\ sec^{-1}$. The existence of strong fluctuations is a characteristic feature of this flare due to which it is, in principle, difficult to determine the value of q from formulas of three-point approximation in spite of sufficiently strong anisotropy. Some fluctuations were also observed for the November 12, 1960 flare. This effect is an indirect proof of the fact that the magnetic field during November 12 and 15, 1960 flares was much stronger than that during the May 4, 1960 flare.

February 23, 1956 flare. Angular distribution of protons with $\mathcal{E}_k \gtrsim 10^9$ ev during the initial stage of this flare was extremely anisotropic. At the same time, the development of flare with time was gradual and significant fluctuations were not observed. Therefore, we can apply to this flare the views [97, 98] that protons with $\mathcal{E}_k \gtrsim 10^9$ ev undergo small-angle scattering due to irregularities of the interplanetary magnetic field and that the kinetic equation in Fokker-Planck approximation can be used to describe their propagation. However, the data on anisotropy of the February 23, 1956 flare is very scanty and therefore, V.I. Shishov limited himself with the study of only N_1 and N_2 - average intensities of particles flying from the Sun and to the Sun respectively. From the point of view of the theory, the same degree of approximation can be obtained for the kinetic equation if the angular spectrum is characterized not by N_1 and N_2 but by intensity n and flux F. Both the pairs of values are related by following relations :

$$\left.\begin{aligned} n &= A(N_1+N_2), \\ F &= B(N_1-N_2), \end{aligned}\right\} \qquad (16.39)$$

where A and B are some numerical coefficients. At sufficiently strong anisotropy, n = AN_1 and F = BN_1, so that very high accuracy of measuring n and F is required in order to get something new from their comparison in addition to the existence of strong anisotropy. At the same time, much lesser accuracy is required for getting the value of q from the comparison of N_1 and N_2 with the help of equation (16.31). Therefore, at the anisotropic stage of a flare, it is more advisable to study the average intensities N_1 and N_2 and not the concentration and flux of particles.

For determining q, it is possible to use a simpler characteristic, namely delay in the appearance of maximum N_2 as compared to appearance of maximum N_1, instead of directly comparing N_1 and N_2. Let us assume that N_1 can be written as

$$N_1 = \begin{cases} C\exp(-t/T_0), & t \geqslant 0, \\ 0, & t < 0. \end{cases} \qquad (16.40)$$

It is a sufficiently good approximation to the reality since the stage of growth of N_1 is very small as compared to the duration of the stage of growth of N2. Putting the equation (16.40) in the equation (16.36), we get

$$N_2 = C\frac{0{,}72q-a}{1{,}44q-2/T_0}\left[\exp\left(-\frac{t}{T_0}\right)-\exp(-0{,}72qt)\right]. \qquad (16.41)$$

Differentiating N2 with respect to t and putting the derivative equal to zero, we get the delay in the appearance of maximum in N_2 as compared to N_1 :

$$t_{\max} = \frac{1}{0{,}72q}\,\frac{\ln 0{,}72qT_0}{1-1/0{,}72qT_0}. \qquad (16.42)$$

If 0.72q T_o is of the order of one, equation (16.42) takes a simpler form

$$t_{\max} = \frac{1}{0{,}72q}. \qquad (16.43)$$

Let us now study the dependence of t_{max} on the energy of particles. As mentioned above, the parameter $q \sim \varepsilon^{-2}$ from which it follows that $t_{max} \sim \varepsilon^2$ i. e., the higher the energy of particles, the more will be the delay in the appearance of the maximum N_2. The position slightly changes on recording particles in some energy range $\varepsilon_1 - \varepsilon_2$. In this case, it is necessary to use the following relation in place of equation (16.36):

$$\bar{N}_2 = \int_{\varepsilon_1}^{\varepsilon_2} N_2(\varepsilon)\,d\varepsilon =$$

$$= \int_0^{t/2}\int_{\varepsilon_1}^{\varepsilon_2} N_1(l_0, t-2\tau, \varepsilon)\exp(-1{,}44q\tau)(0{,}72q\tau-\alpha)\,d\varepsilon\,dt. \quad (16.44)$$

As earlier, we will assume that N_1 can be put in the form (16.39) To simplify the problem let us assume that $\alpha = 0$ (i.e., divergence of the lines of force of the regular field is equal to zero) and $\varepsilon_2 / \varepsilon_1 = 3$. Numerical calculations [118] show that it is possible to take $q(\varepsilon_1)$ as the effective value of $q(\varepsilon)$ at $q(\varepsilon_1)\,T_0(\varepsilon_1) = 1$ and it is also possible to use (16.38). On increasing $q(\varepsilon_1)$, the dependence of t_{max} on q is less than that expected from formula (16.37) and consequently, t_{max} depends on ε to a small extent.

In spite of the large number of stations which had observed the February 23, 1956 flare, the data on anisotropy is very scanty due to following reasons : firstly, almost all the stations were situated at low latitudes and had wide asymptotic cones; secondly, they had different cut-off rigidities which have a significant effect on the fluxes being recorded; thirdly, there were very few stations equipped with similar apparatus. As a result, V.I. Shishov [118] could find only a small number of stations which recorded the flare in the same energy range. Two groups were selected out of all the experimental curves described in [I. 1]. The first group contains data of neutron monitors installed at Leeds, Climax and Chicago stations while the second group includes data of ionization chambers installed at Moscow, Sverdlovsk, Cheltnem, Derwood and Khobart stations. The European stations showed maximum intensity and therefore, their data can approximately be taken as N_1. Data of American stations can be approximately taken as N_2. The effective value of the characteristic time of decrease in intensity T_0 was found to be equal to 35 minutes on the basis of the data of neutron monitors. According to the data of ionization chambers, $T_0 = 25$ min. Thus, this flare better corresponds to the model $T_0(\mathcal{E}) =$ const than to the model $T_0(\mathcal{E}) \sim \mathcal{E}^{-2}$. For neutron monitors $t_{max} = 25$ min from where $q(\mathcal{E}_1) = 0.2$ min^{-1} where $\mathcal{E}_1$ is mainly defined by the cut-off rigidity and is of the order of 2×10^9 ev. For ionization chambers, $t_{max} = 20$ min and $q(\mathcal{E}_2) = 0.07$ min^{-1} at $\mathcal{E}_2 = (3\text{-}4) \times 10^9$ ev. Thus, the obtained values of q are in line with the dependence $q \sim \mathcal{E}^{-2}$. It should, however, be kept in view that these are the average values for different intervals and can effectively be related to distances of 1.3 a.u. and 1.5 – 2 a.u. for neutron monitors and ionization chambers respectively. On the basis of the nature of time of decrease in the intensity of particles, flying from the Sun, L.I. Dorman [I. 5] found that transport range Λ of relativistic particles, which can be recorded by ionization chambers, is equal to $(1\text{-}8) \times 10^{11}$ cm for distances of $(2\text{-}5) \times 10^{12}$ cm from the Sun. Near the Earth's orbit, the transport range $\Lambda \approx 10^{13}$ cm. Thus, Λ increases significantly with distance. From the sloping section of the curve in diffusion approximation, L.I. Dorman [I. 5] also found that $\Lambda = 0.5 - 1$ a.u. This value of Λ is the average value for the range in which are included the internal (with respect to the Earth's orbit) as well as external parts of the interplanetary space.

With the aid of the method described above, V. I. Shishov [118] determined the values of Λ for particles of energy $\gtrsim 2 \times 10^9$ ev at different distances from the Sun during the flares of February 23, 1956, May 4, 1960, November 12 and 15, 1960 (Table 16.1).

It is seen from the Table that the mean free path is either comparable to or more than the distance from the Sun. Naturally, the diffusion approximation is not applicable at such high value of Λ.

The most-detailed information on mean free path was obtained for the May 4, 1960 flare since it possessed maximum anisotropy and since its angular spectrum was studied thoroughly It is seen that Λ during this flare increases with distance as r^2 or even more rapidly.

TABLE 16.1

Mean free path of protons with $\mathcal{E}_k \gtrsim 2\mathrm{x}10^9$ ev at different distances from the Sun

Date of flare	Λ , cm	Distance from the Sun, a. u.
February 23, 1956	3×10^{12}	1.3
May 4, 1960	10^{13}	0.8
	3×10^{13}	1.0
	$>0.8 \times 10^{14}$	2.0
November 12, 1960	3×10^{13}	1.5
November 15, 1960	3×10^{13}	1.5

If the value of irregular magnetic field is given, value of 'a' -- characteristic radius of irregularities -- can be determined from the expression for q. Considering that $\sqrt{H_1^2} = 10^{-5}$ gauss, we get 'a' = 3×10^{10} cm at the Earth's orbit for the May 4, 1960 flare. Basing upon the rocket data, it can be expected that the field can hardly change by more than 3 times. Therefore, the obtained value of 'a' differs from the actual value by not more than one order.

L.I. Dorman and L.I. Miroshnichenko [64] evaluated the dimensions of irregularities for the September 28, 1961 flare on the basis of diffusion theory (see Section 14.4). At a porosity of the interplanetary field of the order of one, the value of the dimension of irregularities $\sim 4 \times 10^{10}$ cm was obtained in [64]. Before comparing these results, it is necessary to mention that 'a' has the significance of characteristic radius. The total dimension of irregularities 2a is equal 6×10^{10} cm. Thus, the dimensions of irregularities obtained for various flares and by various methods differ by less than one order. Practically, they can be considered to be constant with an accuracy of 30-50%.

It is interesting to compare the dimensions of magnetic irregularities with the dimensions of irregularities of electron concentration. Recently, T.D. Antonova et al. [119] and Hewish [120] showed on the basis of scintillation of radio sources that the dimension of irregularities of electron concentration is equal to 10^8 cm. In the view of V. I. Shishov [117], the existence of a wide spectrum of irregularities in the interplanetary space is one of the possible reasons of such large differences in dimensions. Since cosmic rays are most effectively scattered by largest irregularities, on analyzing flares, we get the dimensions characterizing these irregularities. Radio waves on the other hand most effectively react on irregularities of smallest dimensions; therefore; it is possible to get information on the other section of their spectrum. However, it is absolutely possible that differences in dimensions of irregularities of electron concentration and magnetic field are real.

16.5. Boltzmann's equation. For analyzing flares of cosmic rays, Fibich and Abraham [49] used the equation describing dynamic behavior of distribution function $f(\mathbf{r}, \mathbf{v}, t)$ in magnetic field $\mathbf{B}$:

$$\frac{\partial f}{\partial t}+\mathbf{v}\,\frac{\partial f}{\partial r}+[\mathbf{v}\times\omega]\,\frac{\partial f}{\partial \mathbf{v}}=\left(\frac{\partial f}{\partial t}\right)_c, \tag{16.45}$$

where $\omega = e\mathbf{B}/mc$ and $(\partial f / \partial t)_c$ describes change in f as a result of collisions. In the case of uniform distribution of fixed scattering centers, this term takes the form

$$\left(\frac{\partial f}{\partial t}\right)_c=n_s\int d\Omega\,\sigma(\Omega,\ v)\,v\,[f(\mathbf{v}')-f(\mathbf{v})], \tag{16.46}$$

where n_s is the density of scattering centers and σ is the scattering cross section. In the case of elastic scattering $|\mathbf{v}'| = |\mathbf{v}|$ where $\mathbf{v}'$ is the vector v scattered in solid angle Ω.

If the magnetic field is very strong, diffusion will be limited only across the lines of force. As a result, solar particles will move mainly along the lines of force while the distribution function will change only along the direction of the magnetic field. Let the uniform magnetic field be directed along z-axis. The usual method of solving equation (16.45) leads to expansion of f(z, v, t) into Legendre polynomials in the velocity space. Since every line of force has cylindrical symmetry, it is possible to write

$$f(z,\ \mathbf{v},\ t)=\sum_l f_l(z,\ v,\ t)\,P_l(\mu), \tag{16.47}$$

where $\mu = \cos\theta$ (θ is the angle between velocity vector $\mathbf{v}$ and direction of the magnetic field). Under some simplifying assumptions, Boltzmann's equation in this case takes the form

$$\frac{\partial f_l}{\partial t} + v\left[\frac{l+1}{2l+3}\frac{\partial f_{l+1}}{\partial z} + \frac{l}{2l-1}\frac{\partial f_{l-1}}{\partial z}\right] = -\nu_l f_l, \qquad (16.48)$$

where ν_l is the frequency of collisions of a particle with irregularities (this parameter is expressed in terms of $P_l(\cos\Phi)$ where Φ is the scattering angle).

Equation (16.48) is an infinite series; it can be solved only under certain simplifying assumption. As an approximation to equation (16.48), it is possible to neglect all the terms with $l \geqslant 2$ by considering them to be small as compared to first two terms.

Let us select an instantaneous point source at r_0 with isotropic distribution of velocities as the initial condition, i.e.,

$$f_l(t=0) = \delta_{l,0}\varphi_0(v)\,\delta(\mathbf{r}-\mathbf{r}_0). \qquad (16.49)$$

It should be mentioned that consideration of a more general initial distribution (for example, prolonged or non-isotropic) cannot have much significance due to the simplifying assumptions made earlier. In diffusion problems, solution at $t \gg \nu^{-1}$, i.e., after a large number of collisions, is usually of great interest. The following expressions valid at $t \gg \sqrt{\beta}(z-z_0)/v$ were obtained in [49] for the first two terms of (16.48):

$$f_0(z, v, t) \sim \frac{\varphi(v)}{\sqrt{4\pi\varkappa t}}\exp\left\{-\frac{(z-z_0)^2}{4\varkappa t}\right\}, \qquad (16.50)$$

$$f_1(z, v, t) \sim \frac{3}{2}\,\frac{z-z_0}{vt}\,f_0(z, v, t), \qquad (16.51)$$

where $\varkappa = v^2/\sqrt{3\nu}$

The expression f_0 in the equation (16.50) is formally similar to the concentration $n(z, t)$ obtained on solving the equation of one-dimensional diffusion at the same initial and boundary conditions. However, the concentration obtained from equation (16.50), i.e.,

$$n(z, t) = 4\pi\int_0^\infty v^2 f_0(z, v, t)\,dv, \qquad (16.52)$$

will be different and is characterized by the dependence of the form of emission spectrum $\varphi(v)$ and on $\varkappa$ as a function of v. It should be mentioned that $\varkappa$ may not always be proportional to v^2 since ν can be a function of v in a medium with scattering cross section σ (Ω , v).

Let us now consider a uniform magnetic field which is not so strong that it can suppress diffusion across the lines of force. As a result, the limitation, imposed on the longitudinal concentration gradient in the case of very strong field, disappears. In place of expansion of f in the form (16.47), let us use a simpler expansion :

$$f(\mathbf{r}, v, t)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l} f_{lm}(\mathbf{r}, v, t)\sqrt{\frac{2l+1}{2}\frac{(l-m)!}{(l+m)!}}P_l^m(\mu)e^{im\varphi}, \quad (16.53)$$

where P_l (μ) are Legendre's connected functions, μ = cos θ and θ and φ are angles of vector v relative to the fixed x-axis which is taken here as the direction of the magnetic field. Boltzmann's equation in this case becomes

$$\begin{aligned}\frac{\partial f_{lm}}{\partial t}&+v\frac{\partial}{\partial z}\left[\frac{l-m}{2l-1}\tilde{f}_{l-1,m}+\frac{(l+m+1)}{2l+3}\tilde{f}_{l+1,m}\right]+\\&+\frac{v}{2}\left(\frac{\partial}{\partial x}-i\frac{\partial}{\partial y}\right)\left[\frac{1}{2l-1}\tilde{f}_{l-1,m-1}-\frac{1}{2l+3}\tilde{f}_{l+1,m-1}\right]+\\&+\frac{v}{2}\left(\frac{\partial}{\partial x}+i\frac{\partial}{\partial y}\right)\left[\frac{(l+m+1)(l+m+2)}{2l+3}\tilde{f}_{l+1,m+1}-\right.\\&\left.-\frac{(l-m-1)(l-m)}{2l-1}\tilde{f}_{l-1,m+1}\right]-im\omega\tilde{f}_{l,m}=-\nu_l\tilde{f}_{l,m}, \quad (16.54)\end{aligned}$$

where

$$\tilde{f}_{l,m}=\sqrt{\frac{2l+1}{2}\frac{(l-m)!}{(l-m)!}}f_{l,m}, \quad (16.55)$$

$$\nu_l=n_s\int d\Omega\cdot v\sigma(\Omega)\left[1-P_l^m(\cos\Phi)\right]. \quad (16.56)$$

Let us break the chain of equations by retaining only those terms which have l = 0 and l = 1 (m = -1, 0, 1). For simplicity, let us assume that the initial distribution is isotropic in the velocity space, i.e.,

$$f_{lm}(t=0)=\delta_{l0}\delta_{m0}\varphi(v)\delta(\mathbf{r}-\mathbf{r}_0). \quad (16.57)$$

In the absence of the regular field ($\omega = 0$), f_{00} takes the form

$$f_{00}(r, v, t) = \frac{3\sqrt{3}\,\varphi(v)\,\nu}{8\pi v^3}\,\frac{d}{dt}\left[\frac{e^{\nu t/2}J_1\left(\frac{\nu}{2}\sqrt{t^2-\frac{3r^2}{v^2}}\right)}{\sqrt{t^2-\frac{3r^2}{v^2}}}\right]. \quad (16.58)$$

where $r^2 = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2$. From the equation (16.58), at $t \gg \sqrt{3}r/v$, we get

$$f_{00}(r, v, t) \sim \frac{\varphi(v)}{(4\pi\varkappa t)^{3/2}}\,e^{-r^2/4\varkappa t}. \quad (16.59)$$

Let us denote the distance between the observation point and the axis of the magnetic field by ξ, i.e., $\xi^2 = (x - x_0)^2 + (y - y_0)^2$. Two cases are clearly differentiated on calculating f_{00} in the absence of a regular field ($\omega = 0$).

a) $\sqrt{3}\,\xi\,\omega/vt \ll \nu$. It corresponds to the condition $\xi \ll r$ (observation point near the axis) or to the long interval of time with respect to the commencement of the event. In this case, f_{00} takes the form

$$f_{00}(r, v, t) \sim \frac{\varphi(v)}{(4\pi\varkappa t)^{3/2}}\,\frac{\omega^2}{\nu^2}\exp\left[-\frac{r^2}{4\varkappa t}-\frac{\xi^2\omega^2}{4\varkappa\nu^2 t}\right], \quad (16.60)$$

where we again have $\varkappa = v^2/3\nu$. Putting $\varkappa_\perp = \varkappa\,\nu^2/(\omega^2+\nu^2)$ f_{00} can be put in a simpler form

$$f_{00}(r, v, t) \sim \frac{\varphi(v)}{(4\pi t)^{3/2}\,\varkappa^{1/2}\varkappa_\perp}\exp\left[-\frac{(z-z_0)^2}{4\varkappa t}-\frac{\xi^2}{4\varkappa_\perp t}\right]. \quad (16.61)$$

b) $\sqrt{3}\,\xi\,\omega/vt \gg \nu$. It corresponds to the condition $\xi =$ $\varrho(r)$ or to the short interval of time relative to the commencement of the event (here, the condition $t \gg \nu^{-1}$ is still satisfied). In this case, the solution will be

$$f_{00}(r, v, t) \sim \frac{\omega^2}{\nu^2}\,\frac{\varphi(v)}{(4\pi\varkappa t)^{3/2}}\left(\frac{\nu t}{2\sqrt{3}}\,\frac{\rho}{\xi}\right)^{3/4}\times$$

$$\times\exp\left[-\sqrt{3}\,\frac{\xi}{\rho}\left(1-2\sqrt{\frac{\nu t}{2\sqrt{3}}\cdot\frac{\rho}{\xi}}\right)-\frac{r^2}{4\varkappa t}\right]. \quad (16.62)$$

This solution is applicable at $\nu^{-1} \ll t \ll \sqrt{3}\,\nu^{-1}\xi/\varrho$ where $\varrho = v/\omega$ is the Larmorov radius of the particle.

Thus, the behavior of the solution is different in the case of short and long intervals of time (in the latter case, there will be three-dimensional diffusion). Consequently, the parameter $t_t = \sqrt{3}\ \nu^{-1} \xi / \varsigma$ can be taken as the characteristic time of transition from the schedule of short intervals to the schedule of long intervals of time. The transition time is directly proportional to the intensity of magnetic field and to the distance of the observation point from the axis.

Anisotropic terms in velocity distribution are approximately defined by the following expression :

$$\left.\begin{aligned} f_{10} &\approx \frac{\sqrt{3}}{2} \frac{z-z_0}{vt} f_{00}, \\ f_{11} &\approx \frac{\sqrt{6}}{4} \frac{\nu^2+\omega^2}{\nu(\nu-i\omega)} \frac{(x-x_0)-i(y-y_0)}{vt} f_{00}, \\ f_{1,-1} &= f_{11}^{*}. \end{aligned}\right\} \qquad (16.63)$$

Thus, the solution of the Boltzmann's equation for the distribution function of solar particles in the interplanetary medium leads to a short-lived process of the type of one-dimensional diffusion which is accompanied by the transition to three-dimensional (isotropic) diffusion. The transition time depends on the intensity of regular magnetic field. The only parameters, which depend upon the rigidity of particles, are the transition time and anisotropic part of distribution function (in the velocity space).

The simplest type of boundary and initial conditions were selected in the work [49] : the flare was represented in the form of an instantaneous point source while the concentration and distribution functions were considered to be finite at zero and zero at infinity. Therefore, the study of the effect of the selection of a finite source as well as the detailed study of the effect of the Sun, taken as the reflecting and absorbing boundary, on the results would be of great interest. The solution for magnetic fields, resembling to the actually observed ones, would have been of still greater interest.

16.6. Motion of cosmic particles in an arbitrary magnetic field. The motion of cosmic particles in the interstellar and interplanetary medium is mainly defined by their scattering at the magnetic fields of the cosmic space. These fields are carried by plasma clouds. Scattering at the moving irregularities of the magnetic field leads to a change in the energy spectrum and in the direction of motion of cosmic particles.

The problem of the motion of particles in the cosmic space is usually studied in diffusion approximation which in most of the real cases is not applicable. Therefore, a more general formulation of the problem is considered in the work of A. Z. Dolginov and I. N. Toptygina [121].

The authors [121] base upon the Boltzmann's equation for noninteracting particles moving in the external magnetic field :

$$\frac{\partial f}{\partial t}+\mathbf{v}\frac{\partial f}{\partial \mathbf{x}}+\mathbf{H}\cdot\mathbf{D}f=0. \qquad (16.64)$$

Here $\mathbf{D} = \frac{e}{c}[\mathbf{v} - \mathbf{u}\frac{\partial}{\partial \mathbf{p}}]$; $\mathbf{p}$ is the momentum, $\mathbf{v}$ is the velocity of a particle, $f(\mathbf{x}, \mathbf{p}, t)$ is the distribution function of particles and $\mathbf{u}$ is the average velocity of magnetic fields relative to the observer ($u \ll c$). Let us assume that the magnetic field has regular $H_0(\mathbf{x}, t)$ and arbitrary $\Delta H(\mathbf{x}, t)$ components : $H(\mathbf{x}, t) = H_0 + \Delta H$ where $H_0 = \langle H \rangle$ and $\langle \Delta H \rangle = 0$. In order to completely characterize the arbitrary magnetic field, it is necessary to know the correlation tensor of the second order

$$\langle \Delta H_\alpha(\mathbf{x}_1, t_1)\Delta H_\beta(\mathbf{x}_2, t_2)\rangle = B_{\alpha\beta}(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) \qquad (16.65)$$

and the whole group of similar tensors of higher orders. Let us select the correlation function for equation (16. 65) in the form

$$B_{\alpha\beta}(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) = B_{\alpha\beta}(\mathbf{r}) \exp\left[-l^{-2}(\mathbf{x}-\mathbf{u}t)^2\right]. \qquad (16.66)$$

Here $\mathbf{r} = (\mathbf{x}_1 + \mathbf{x}_2)/2$; $\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_2$; $t = t_1 - t_2$ and ℓ is the average size of irregularities of the arbitrary field. The parameter $B_{\alpha\beta}(\mathbf{r})$ describes the change in the mean square of the field while the exponential term describes the uniform motion of irregularities at a velocity $\mathbf{u}$. We will assume that $\mathbf{u}$ is directed along $\mathbf{r}$-vector. Let us denote the Larmorov radius of a particle in the arbitrary field by $\rho = cp/e\langle \Delta H^2 \rangle^{1/2}$ and the characteristic length, at which $\mathbf{u}$ and $B_{\alpha\beta}(\mathbf{r})$ change significantly, by L. Let us consider the case when $L \gg \ell$ and $\rho \gg \ell$. It means that the particle gets scattered at the irregularities of the field without any significant deflection during each scattering. Therefore, all the terms corresponding to correlators of orders higher than the equation (16.65) can be neglected. Summing up the remaining terms, we get the kinetic equation for the distribution function averaged for the arbitrary field. Let us write this equation in the coordinate form for the case when $cp/eH_0 \gg \ell$:

$$\left[\frac{\partial}{\partial t}+\mathbf{v}\frac{\partial}{\partial \mathbf{r}}-\mathrm{H}_0\mathrm{D}+\frac{\sqrt{\pi}}{2}\,l\sum_{\alpha,\beta}D_\alpha\frac{B_{\alpha\beta}(\mathbf{r})}{|\mathbf{v}-\mathbf{u}|}D_\beta\right]F(\mathbf{r},\mathbf{p},t)=0, \quad (16.67)$$

where $f(\mathbf{r}, \mathbf{p}, t) = \langle f(\mathbf{r}, \mathbf{p}, t) \rangle$

In order to get the diffusion approximation, let us expand F into Legendre's polynomial for angles determining the direction of **p** and limit ourselves with the first two terms of the expansion :

$$F(\mathbf{r},\mathbf{p},t)=\frac{1}{4\pi}\left[N(\mathbf{r},\mathbf{p},t)+\frac{3}{v^2}\mathbf{v}\cdot\mathbf{I}(\mathbf{r},\mathbf{p},t)\right], \quad (16.68)$$

where N and **I** are new unknown functions not depending on the direction of **p**. Putting equation (16.68) in equation (16.67) and after simple transformations, we get a system of equations for N and **I**. For the steady case when $u \ll v$, we get u = const, $H_0 = 0$ and $B_{\alpha\beta}(r) = 1/3\langle \Delta H^2(r)\rangle \delta_{\alpha\beta}$. This system is of the form

$$\operatorname{div}\mathbf{I}=\frac{(mc)^2}{\Lambda(\mathbf{r})}\left[\frac{u^2}{3v}\frac{\partial^2 N^0}{\partial p^2}+\frac{2u^2}{3pv}\left(1-\frac{m^2c^4}{3\varepsilon^2}\right)\frac{\partial N}{\partial p}+\right.$$
$$\left.+\frac{1}{\rho v}\mathbf{u}\frac{\partial \mathbf{I}}{\partial p}+\frac{c^2}{\varepsilon^2 v}\mathbf{u}\mathbf{I}\right], \quad (16.69)$$

$$\mathbf{I}=-\frac{v\Lambda(\mathbf{r})}{3}\left(\frac{p}{mc}\right)^2\frac{\partial N}{\partial \mathbf{r}}-\frac{p\,\partial N}{3\,\partial p}\mathbf{u}, \quad (16.70)$$

where $\Lambda(r) = 3(mc^2)^2/\sqrt{\pi}\, e^2 \ell \langle \Delta H(r)\rangle$. Right-hand part of the continuity equation (16.69) contains the terms describing change in the energy of particles due to their collisions with the moving irregularities. These terms become equal to zero after integrating along all the values of p. The equation (16.70) defines diffusion flux. The paramter

$$\varkappa(\mathbf{r},p)=\frac{v\Lambda(\mathbf{r})}{3}\left(\frac{p}{mc}\right)^2 \quad (16.71)$$

represents diffusion coefficient. The expressions obtained for the diffusion flux significantly differ from the expression used in the work of Parker [18] :

$$I = -\varkappa \frac{\partial N}{\partial r} + Nu. \tag{16.72}$$

Formula (16.72) is applicable only on satisfying two conditions : 1) if $\varkappa$ does not depend on the energy of particles and 2) if N is the total concentration of particles of all energies. The application of equation (16.72) for calculating the energy spectrum of diffusing particles (see for example, [18] or the work of Terashima [122] is not correct.

For the spherically symmetrical cases, on assuming that $\varkappa$ does not depend on r and $\mathcal{E} \approx cp \gg mc^2$, from (16.69) and (16.70), we get the following diffusion equation :

$$\varkappa(p)\left(\frac{\partial^2 N}{\partial r^2} + \frac{2}{r}\frac{\partial N}{\partial r}\right) - u\left(\frac{\partial N}{\partial r} - \frac{2p}{3r}\frac{\partial N}{\partial p}\right) = 0. \tag{16.73}$$

If the diffusion takes place in space where there are moving regions with a strong magnetic field in which the particles penetrate only to a small depth (the case opposite to the one considered above), the equation (16.73) still remains valid but $\varkappa$, obtained from the kinetic equation, does not depend on p. In this case, an accurate solution of (16. 73) can be obtained in the form of a series with the help of the degenerated hypergeometric functions. As an example, let us mention the solution of equation (16. 73) at $\varkappa$ = const which may satisfy the boundary condition $N(r_0, p) = N_0(p_0^{\gamma}/p)$ at $p > p_0$ and $N(r_0, p) = 0$ at $p < p_0$ where r_0 is the boundary of the region in which $u \neq 0$:

$$\left.\begin{aligned} N(r, p) &= N_0 \frac{\Phi\left(\frac{2}{3}\gamma, 2, \frac{u}{\varkappa} r\right)}{\Phi\left(\frac{2}{3}\gamma, 2, \frac{u}{\varkappa} r_0\right)} \left(\frac{p_0}{p}\right)^{\gamma}, \quad r \leqslant r_0, \quad p \geqslant p_0, \\ N(r, p) &= N_0 \sum_{n=0}^{\infty} \frac{\Phi\left(-a_n, 2, \frac{u}{\varkappa} r\right)}{\left(a_n + \frac{2}{3}\gamma\right)\Phi'_{r_0}\left(-a_n, 2, \frac{u}{\varkappa} r_0\right)} \left(\frac{p}{p_0}\right)^{\frac{3}{2}a_n}, \\ & r \leqslant r_0, \quad p < p_0. \end{aligned}\right\} \tag{16.74}$$

Here Φ is the degenerated hypergeometric function; a_n are the roots of the equation $\Phi(-a_n, 2, \frac{u}{\varkappa} r_0) = 0$ and $\Phi'_{r_0} = \partial \Phi /$

$/\partial r_0$. As it follows from the equation (16.74), the ratio $y(r) = N(r, p)/N(r_0, p)$ does not depend on p at $p \gg p_0$. Continuous curves in Fig. 16.6 give the dependence y(r) at $\gamma = 4.5$ and the values of parameter $k = ur_0/\varkappa$ equal to 0.5, 1.0, 2.0 respectively. The selected value of γ corresponds to the spectrum $N(r_0, p)p^2dp \sim \mathcal{E}^{-2.5}\, d\mathcal{E}$ ($\mathcal{E} \approx cp$) at the boundary of the solar system. Values of y(r) calculated at the same values of γ and k with the help of formula (16.72) are also given in the same Fig. for calculation purposes. It is seen that the error caused by the inaccuracy of formula (16.72) can change the result by many times. The value $k \approx 1$ is obtained by assuming that $u \approx 1000$ km/sec, $r_0 \approx 50$-100 a.u., $\ell \approx 10^6$ km and $\langle \Delta H^2 \rangle^{1/2} \approx 10^{-4}$ gauss. However, in the case of protons with an energy of a few Gev, the Larmorov radius ρ in the quasiregular field of magnetic cloud is of the order of ℓ and therefore, the condition $\varkappa$ = const is satisfied only approximately. On increasing the energy of particles, the diffusion coefficient given by equation (16.71) increases and at $\rho \gg \ell$, it becomes proportional to p^2 while at nonrelativistic energies and $\rho \ll \ell$, it is proportional to p. Therefore, in order to obtain results which could be compared with the experiment, it is necessary to consider the dependence of diffusion coefficient on the energy of particles.

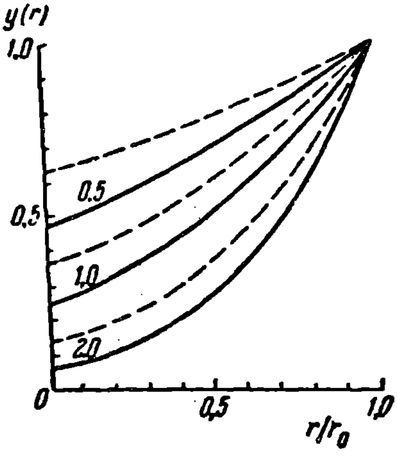

Fig. 16.6. Dependence of y(r) on r/r_0 at $\gamma = 4.5$ and $ur_0/\varkappa = 0.5$, 1.0 and 2.0 (continuous curves). Dotted curves - values of y(r) calculated from formula (16.27).

The effect of regular magnetic field and of fluctuations in the velocity of solar wind on the motion of cosmic rays is briefly discussed in the work of A.Z. Dolginov and I.N. Toptygina [123]. The existence of these factors was recently confirmed by direct measurements. It can be assumed on the basis of the data of Wilcox and Ness [III. 137], that the magnetic field in the Earth's orbit is more or less orderly and has sectorial structure. Turbulization of plasma and transition to disorderly field apparently take place beyond the Earth's orbit at distances of a few a.u. from the Sun. On the other hand, measurements of K.I. Gringauz et al. [124] show that the value and direction of the velocity of solar wind fluctuate and that Δu can be of the same order as u_0 - the average rate of motion of magnetic irregularities.

Let us first of all consider the above-mentioned factors, namely regular field H and change in velocity Δu, within the framework of diffusion equation. Here we will assume that the regular field does not move at a velocity u and therefore, there is no regular electrical field in the reference system associated with the Sun. In this case, diffusion equation, obtained from kinetic equation (16.67), takes the form

$$\frac{\partial N}{\partial t} = \nabla_\alpha \varkappa_{\alpha\beta} \nabla_\beta N - \mathbf{u}_0 \nabla N + \frac{1}{3}(\nabla \mathbf{u}_0) p \frac{\partial N}{\partial p} + \\ + \frac{\Delta u^2}{9\varkappa_0}\left[p^2 \frac{\partial^2 N}{\partial p^2} + \left(3 + \frac{v^2}{c^2} - \frac{p}{\Lambda}\frac{\partial \Lambda}{\partial p}\right) p \frac{\partial N}{\partial p}\right]. \quad (16.75)$$

Here $\Delta u^2 = u_0^2$ and $\varkappa_{\alpha\beta}$ is the anisotropic diffusion coefficient. In the system of coordinates, the z-axis of which is directed along H and the tensor $\varkappa_{\alpha\beta}$ has components different from zero:

$$\varkappa_{11} = \varkappa_0; \quad \varkappa_{22} = \varkappa_{33} = \frac{\varkappa_0 \rho^2}{(\rho^2 + \Lambda^2)}; \quad \varkappa_{32} = -\varkappa_{23} = \frac{\varkappa_0 \Lambda \rho}{(\rho^2 + \Lambda^2)},$$

where ρ = cp/eH is the Larmorov radius of the particle in the regular field, Λ is the transport range and $\varkappa_0 = v\Lambda/3$. In the case of a small angle of scattering at one magnetic cloud, we have

$$\Lambda = 6c^2p^2/\sqrt{\pi}\, e^2 l \langle H_1^2(r)\rangle, \quad (16.76)$$

where l is the size of the cloud and $\langle H^2 \rangle$ is the mean square of the arbitrary field. However, the equation (16.75) is valid even in the case when the particles are scattered through an arbitrary angle. In this case, in place of the equation (16.76), we will have $\Lambda = [Cg(p)]^{-1}$ where C is the concentration of magnetic clouds and $g(p) = \int (1-\cos\theta)\,d\sigma$ is the scattering cross section of a particle at one cloud.

The solution of the equation (16.75), not depending upon time, can easily be found in the absence of regular field at $\varkappa_0 =$ const, Δu^2 = const and u_0 = const. In the ultrarelativistic case when spectrum is of the form $d\mathcal{E} / \mathcal{E}^{2.5}$, the concentration of particles will be $N = f(r)\,(p_0/p)^{4.5}$ where p_0 is a constant. The dependence of N on Δu is shown in Fig. 16.7. It is seen that consideration of change in the velocity of solar wind insignificantly changes the value of N.

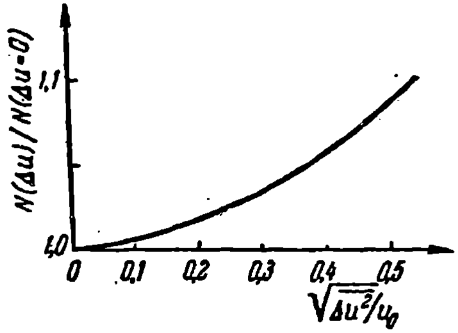

Fig. 16.7. Dependence of the concentration of cosmic particles near the Earth's orbit on the ratio $\sqrt{\overline{\Delta u^2}}/u_0$ *at* $u_0 r_0/\varkappa_0 = 2$.

The transport range Λ depends on the coordinates and energy of the particle. In the case of small scale irregularities, it is proportional to p^2; in the other extreme case when the field of magnetic clouds is strong and the particles penetrate in them only to a small depth, Λ does not depend on p. It is natural to assume that the second case must be observed for low-energy particles (see Section 14.4). But it may not be so in the presence of a significant regular component of the magnetic field.

A magnetic irregularity functions as a scattering center at the condition $l \ll \rho$ as well as in the case of a large gradient of the field. If the field of magnetic cloud is not large and changes gradually, the particle will mainly move in the direction of lines of force of the regular field which are slightly distorted due to existence of the arbitrary component of the field. The model of guiding center and not the diffusion equation (16.75) is more suitable for explaining the motion of particles in this case. Here, it may happen that penetration of low-energy particles in the solar system is eased as compared to high-energy particles.

The particles can move along the lines of force even in the absence of the regular field if the arbitrary field is sufficiently strong at all places and changes insignificantly at distances of the order of ρ . The lines of force of the magnetic field in this case will be distorted in an arbitrary way and the motion of particles will be defined by statistics of the lines of force. Some qualitative estimates for such a case as applicable to the motion of cosmic rays in the Galaxy were made by G. G. Getmantsev [113] but the successive theory is absent.

If there are small irregularities, functioning as stationary scattering centers, in the background of a strong and gradually changing magnetic field, the distribution function of the particles satisfies the equation

$$\frac{\partial F}{\partial t} + \mathbf{v}_d \frac{\partial F}{\partial r} + \Phi(\mathbf{r},\ \theta)\frac{\partial F}{\partial \theta} =$$

$$= \frac{v}{2\Lambda \sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial F}{\partial\theta} + \frac{\rho^2 v}{\Lambda}(1+\cos^2\theta)\,\Delta_{\perp}F. \quad (16.77)$$

Here Λ is determined from formula (16.76) while $\Delta_{\perp}$ is Laplace operator functioning in coordinates transverse with respect to $\bar{\mathbf{H}}$, θ is the pitch angle of the particle and $\mathbf{h} = \frac{\mathbf{H}}{H}$

$$\mathbf{v}_d = \left(v\cos\theta + \frac{v\rho}{2}\sin^2\theta\,\mathbf{h}\operatorname{rot}\mathbf{h}\right)\mathbf{h} + \frac{v\rho}{2}\sin^2\theta\left[\mathbf{h}\times\frac{\nabla H}{H}\right] +$$

$$+ v\rho\cos\theta\,[\mathbf{h}\times(\mathbf{h}\nabla)\mathbf{h}], \quad (16.78)$$

$$\Phi(\mathbf{r},\ \theta) = -v\sin\theta\operatorname{div}\mathbf{h} + v\rho\sin\theta\cos\theta\left(\frac{\nabla H}{H}[\mathbf{h}\times(\mathbf{h}\nabla)\mathbf{h}] +\right.$$

$$\left. + \mathbf{h}\operatorname{rot}(\mathbf{h}\nabla)\mathbf{h}\right). \quad (16.79)$$

Expression (16.77) is the drift equation, supplemented by terms describing collisions. Apparently, this equation describes the motion of cosmic rays at a distance of a few a.u. from the Sun where regular component of the field is large and the irregularities play an insignificant role. At distances, significantly more than Λ , along the lines of force of the magnetic field, distribution function F depends on θ to a small extent and equation (16.77) changes into the equation (16.75) on reaching the limit $\varrho << \ell$ and on putting $u_0 = \overline{\Delta} u^2 = 0$ in the latter equation. Under these conditions, motion of particles attains the nature of diffusion with extremely anisotropic diffusion coefficient $\varkappa_{\alpha\beta}$.

Before the end this Chapter, it should be mentioned that the problem of propagation of solar cosmic rays, and the problems discussed above are far from being exhaustive. It is appropriate to mention here that the above-mentioned basic views on this problem get, with every year, more and more verified experimentally owing to direct measurements in the interplanetary space as well as owing to the results of investigations on interconnected problems. For example, it may be pointed out that good agreement has been observed between the values of the intensity and structure of the interplanetary field, obtained from the analysis of 11-year variations in galactic radiation, from the analysis of flares of solar cosmic rays and from direct magnetic measurements in the interplanetary space.

It is also necessary to mention the rigid relation between propagation of solar particles and modulation of cosmic rays- - daily anisotropy, Forbush effects, 11-year variations (determination of life of irregularities, possibility of accumulation of low-energy particles in the interplanetary space, low-latitudinal cut-off of cosmic rays, distribution of irregularities in the interplanetary space, etc.).

CHAPTER V

SOME PROBLEMS OF THE PHYSICS OF SOLAR FLARES AND GENERATION OF COSMIC RAYS ON THE SUN

In order to understand the generation of solar cosmic rays, observations on chromospheric flares and the phenomena accompanying them are extremely important. Let us mention some of the most important aims of these observations.

1. Investigation on the characteristic features of the groups of sunspots in which the flares takes place. The establishment of the changes in characteristic features of a flare and the magnetic fields after a flare is one of the fundamental results of such an investigation.

2. Nature of such phenomena, accompanying solar flares as "whiskers", activation of fibers, loop protuberances flocculations, etc. Problems of predicting solar flare are related to these very phenomena.

3. Study and interpretation of radio and X-ray radiation of flares which helps in obtaining information on the nature of acceleration processes on the Sun. Radio radiation of type IV is of special importance since it helps in locating the acceleration region in the flare as its source in the beginning has small angular dimensions.

4. Peculiarities of chromospheric flares accompanied by an increase in the intensity of cosmic rays.

17. OBSERVATIONS AND CLASSIFICATION OF SOLAR FLARES

17.1 Peculiarities of active regions and origin of flares. From the observations on solar-flare phenomena, first of all, follows the conclusion that the appearance of groups of sunspots is the necessary condition for flares.

The relation N = bW between the number of solar flares N and the number of sunspots W was obtained in the work of Swestka [1]. In the recent past, this result was confirmed by Ellison et al. [2] on the basis of IGY data. A.B. Severnyi [3] mentions the following characteristic features of origin of flares in the groups of sunspots: 1) flares originate at neutral points of the Sun's magnetic field; 2) the appearance of flares is related to the origin of a strong gradient of magnetic fields in the region of the neutral point; 3) the characteristic mutual redistribution of the field after a flare.

While studying the development of sunspots, Jakimiec [4], from the comparison of isolated spots and spots of bipolar groups, found that the values of parameter C, characterizing the shape of a spot, have smaller deviations from the average value for isolated spots than for spots of bipolar groups, i.e., isolated spots have high "stability of shape". Evans [5] and Smith [6] observed similar characteristics of flares. However, Michard et al. [7] as well as Howard and Babcock [8] mention that significant quantitative changes in the Sun's magnetic field were not observed during class 1^+ flare. Later on, Reid [4] found that changes in the characteristic features of chromosphere and magnetic field do not at all exist during weak flares.

Caroubalos [10] found an interesting result of the investigation on centers of solar activity. He mentions that parameter d/D as a characteristic of the centers of activity where d is half the distance between edges of penumbra of the spots of opposite polarity and D is the diameter of the spot. This parameter is related to intensity of horizontal field and gradient of longitudinal field. It was found that the groups of spots where flares, followed by outbursts of radio radiation and geophysical effects occur, are characterized by minimum values of this parameter.

While studying the development of group spots, A.N. Koval' [11] found that the process of formation, development and disintegration of spots is directly related to the phenomena of "whiskers" and ejections. The presence or absence of movements in the region of "whiskers" depends on the stage of development of group spots. It follows from visual observations that ejections usually precede formation of spots and are observed to the maximum extent during the initial period of the group's life. It is concluded on the basis of the observed movements in the region of "whiskers" that asymmetry is apparently related to attenuation of emission of "whiskers" in one of the wings owing to ejection of the matter.

Yu. I. Vitinskii [12] describes some of the peculiarities of the centers of solar activity. It has been shown that the distribution of centers along heliographic longitude significantly differs from arbitrary distribution. The dependence of duration of centers on heliographic longitude was not observed. From the study of 64 developing groups of spots, 3 types of curves of increase in area were obtained and it was established that the nature of this increase is defined by the value of maximum area of a group and by its class (according to dynamic classification). It was established that class 2 and 3 flares and, very rarely, the maximum area of the group is the determining factor for the duration of a center of activity. On the above basis, an attempt has been made to classify centers of activity.

Elliot and Reid [13] have described the movement of centers of activity on the Sun's disk during September 14-26, 1963. The development of class 3 flare on September 26, 1963 is also described in the work. The flare was accompanied by emission of cosmic rays of comparatively low energies (10-400 Mev). On the basis of the comparison of this flare with others, it was assumed that the absence of high-energy particles in this case is related to peculiarities of magnetic field in the dying group of spots.

For understanding the peculiarities of the origin of flares, Bruzek's work [14] is of great interest in which the relation between flares and loop protuberances is studied. Statistical processing of observational data shows that all the loop protuberances are related to large flares. Out of 25 loop protuberances observed on the disk during 1956-63, 20 were related to class 3 and 3^+ flares while 5 to class 2 and 2^+ flares. Apparently, solar protuberances represent a part of one phenomenon of the flare leading to spreading of flare process from the chromosphere to the corona. On the basis of these observations, Bruzek [14] suggested the following schematic model of development of flare and loop protuberances in H_α lines:

1. A few small bright knots appear on the disk; growing together, they gradually form a bright thread after 10-15 minutes. Development on the limb starts with the appearance of flare undulations spreading at a rate of 10-15 km/sec.

2. After about 30 minutes, a flare spreading at a rate of about 10 km/sec is seen on the limb, in which it is possible to distinguish loop structure and internal movement (spreading fiber of the flare).

3. About 50 minutes after the commencement of flare on the limb, loop structure widening at a rate of 5-10 km/sec is observed clearly. The flare on the disk attains maximum brightness and gets divided into two parallel fibers diverging at a rate of 5 km/sec.

4. After $\geqslant 3$ hours, the flare disappears on the disk, the loop system on the limb continues widening at a rate of 2 km sec and gets divided slowly and finally disappears after 12 hours.

An attempt was made by Fokker [15] to interpret the phenomena observed by Bruzek [14]. Owing to the fact that dynamic properties of protuberances are apparently related closely to the changes in the intensity of magnetic field or in the configuration of the lines of force, Fokker studies the configuration of magnetic field of two dipoles rotating in an ideal plasma. If the dipoles are stationary and antiparallel, they are connected by lines of force. It is shown that if the antiparallel dipoles start rotating in opposite directions in a plane passing through the axis of dipoles, the loop of lines of force, connecting dipoles, starts widening. In this case, each elementary volume of plasma will be displaced in the direction of widening of the loop; i.e., perpendicular to the direction of lines of force of the magnetic field. We, however, feel that dynamic processes related to the origin of loop protuberances have more complicated nature. This question will be discussed in Section 18.

Valniček [16] classified the escape of matter from active regions on the basis of the motion of escaped matter by considering the characteristics of the surrounding active region. He differentiated 3 types of processes.

1. Isolation of a part of the flare which resembles to an explosion and lasts for $\lesssim 10$ minutes. At the later stage of this process, there is usual eruptive protuberance with disappearance of the matter back in the chromosphere.

2. "Blowing out" of protuberances characterized by prolonged existence in the quiet state with period of the active stage equal to a few tens of minutes. These protuberances appear in the regions where there are no flares and spots.

3. Flare with explosive phase and activation of fibers.

It is shown that in the first and third cases, escape of matter from the flare region has explosive nature and the process itself is defined by the degree of activity of the region where the phenomenon takes place. Escape of matter in the second case has another nature. It is caused by the suddenly-appearing stable distance of a protuberance apparently related to the total magnetic field of the Sun.

Problems of predicting solar flares were considered in the work of Waddell [17]. He worked out a statistical method of predicting powerful flares during 21-35 days. The method is based on the correlation between calcium floccules at the given revolution of the Sun and flares during the subsequent revolution. The probability of a flare depends upon the area, brightness and age of the flocculated field. It is established that, if the zero points of the magnetic field remain stationary for 3 days or more, a flare may be expected in the given region during the next revolution of the Sun.

The relation of flares to stationary neutral points of the magnetic field is considered in another work of Waddell [18].

For flares having an area of not less than 100 millionth part of the solar hemisphere (period 1959-60), a relation between their position and structure of magnetic field at the level of photosphere during 1 revolution of the Sun before the flare, has been established from the data of Sacramento-Peak and Mount-Wilson observatories. In 22 out of 51 cases, the position of the flare coincided with the neutral point which existed at this place in the previous revolution. The field in the neighboring regions was more than 10 gauss. Retainability of neutral points during 1.5 revolution of the Sun was investigated on the basis of another control selection of 62 out of 80 cases of flares. The author arrives at the conclusion that the appearance of a flare, with an area more than 100 millionth part of hemisphere in the given magnetic region, during the next revolution of the Sun can be predicted with a probability of 0.43 if : 1) the neighboring fields $B_{\parallel}$ are more than 4 gauss; 2) $\partial B_{\parallel}/\partial t$ is less than 1 gauss/day; 3) gradient of $B_{\parallel}$ is more than 10 gauss/degree. On combining this method with the optical method (comparison with flocculated areas), justification of the prediction is evaluated at 0.79.

The observed effects of accumulation and liberation of magnetic energy during solar flares are analyzed in Schmidt's work [19].

A classification of possible changes in the magnetic field of the Sun's active region according to the observed effects, caused by these changes, has been suggested. It is shown that distribution of normal component of the magnetic field on the surface of the Sun's active region makes it possible to determine the potential field over the surface and to evaluate the total magnetic energy in space. In order to study the changes in the magnetic field during flares, 10 photospheric magnetic maps of the active region were used which were obtained on the magnetograph of the Crimean Astrophysical Observatory during July 14-18, 1959. During this period, three large flares took place in the region the most powerful of which (class 3^+) was observed on July 16, 1959. Changes in the total magnetic flux Φ and in the surface magnetic energy W of section under reference as well as the total energy U of the magnetic field in atmsophere over this section were determined from the magnetic maps. Significant and rapid changes in Φ, W and U were detected and the nature of change of all the three parameters was the same. Increase of Φ, W and U before the July 16 flare and the sudden decrease (by one order) after the flare have been noted. Two independent parameters are suggested for characterizing the space distribution of magnetic field of the region under reference: $H = U/W$ characterizing the extent of field in the vertical direction and

$R = \phi^2/U$ characterizing the concentration of flux in photosphere. With the passage of time, these parameters increased slightly but did not undergo any significant changes. It shows that large changes in the value of flux during a flare are not accompanied by corresponding changes in the geometrical flux distribution. Owing to large conductivity of the solar atmosphere, changes in flux cannot be related to dissipation or diffusion of magnetic lines of force but are determined by the motion of matter. However, change in flux by retaining the geometry of the field points out such a relation between the field of velocities and magnetic field which appears to be less probable.

M.B. Ogir and E.F. Shaposhnikova [20] mentioned one more interesting peculiarity of flares in groups of sunspots. They showed that the appearance of powerful flares is often preceded by new spots originating in the group or by intensification of spots earlier existing near the place of flare.

New data on peculiarities of solar flares, their relations with configuration of spots and injection of protons are described in the works of Dodson and Hedeman [21] and Warwick [22].

17.2. Radio and X-ray radiation of flares. Let us now consider briefly some of the problems related to radiation from flares. As mentioned above, observations on radio emission of type IV are very important for understanding the mechanisms and for determining the regions of acceleration of cosmic rays in flares. Avignon et al. [24] showed that flares, accompanied by this type of radio emission, appear in the active regions consisting of very close spots of opposite polarity, i.e., under the conditions favorable for generation of particles. Boischot and Pick [24] found that radio emission of type IV gives rise to synchrotron radiation of relativistic electrons being accelerated in flares and rotating in magnetic fields along spirals. This hypothesis was recently verified by Fichtel et al. [25].

Sakurai [26] pointed out that energy of solar protons is closely related to the energy of electrons responsible for outbursts of type IV in lower corona and also described the nature of flare-nimbus phenomenon accompanied by this type of radio emission. He showed that flare-nimbus is caused by energetic electrons trapped in sunspots by magnetic field after injection of electrons by flares. On the basis of the study of radio emission of type IV, Sakurai [27] found in another work that magnetic field of sunspots has the structure of a magnetic dipole inclined to the west and situated under the photosphere and that flares mainly occur in the eastern part of the spot. These magnetic fields surround the flare region and form arc-type lines of force related to the main spot, in the magnetic field of which, the electrons are retained after injection in the flare.

X-ray radiation of $\lambda < 8Å$ is also closely related to flares. Friedman [28] has given the available data on X-ray radiation and sudden ionospheric disturbances (SID) in the ionosphere including the results of observations on X-ray on satellites "SR-1", "SR-16", "UK-1", "SR-3" and the Soviet satellites. Theoretical investigations on X-ray spectrum of the solar-flare radiation and its effects on ionization in the D-layer of the ionosphere are also described in this work.*

The structure of active regions on the Sun, responsible for the variable part of short-wave radiation of the Sun, is studied by Allen [26]. The results of calculations of retarding, recombination and linear radiation are described in the work on

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At the International Sympossium on Solar Activity (Budapest, September 1967), American research workers Neupert, Tausy, Aktyon and others presented latest data on X-ray radiation and solar cosmic rays measured on "OGO" satellites. A number of slitless spectroheliograms have been obtained in the range 20-400 Å in which the increase in brightness is observed not only near the edge of the disk but also in the region of protuberances. A significant increase in the intensity of radiation over active regions was observed in the spectral range of 1-25 Å. Emission lines in the extreme X-ray region (2-12 Å) and a number of new lines -- Ni, Fe and others -- in the range of 13-64 Å were observed for the first time. It was possible to get a number of spectograms in this range during powerful flare of the May 25, 1967. The time of attaining maximum intensity in different X-ray lines is intermixed: in the beginning, maximum is achieved in the extremely short-wave line and afterwards, in the long-wave lines. The interval between maxima varied from about 1 minute to tens of minutes. It is characteristic that the duration of illumination of flare in these emission lines is very large (of the order of the duration of illumination in the optical region). Since optical thickness for short-wave lines is much less than unity, the prolonged illumination in X-ray lines indicates relatively prolonged liberation of energy during a flare. This absolutely new result does not agree with any existing hypothesis of "instantaneous" energy liberation owing to "annihilation" of magnetic field, during the flare, in the region of neutral points.

the basis of the presented experiemental data on radiation of solar flares in the region $\lambda \angle 10$ Å.

While studying outbursts of X-ray during September 28, 1961 flare, A.A. Korchak [IV. 99] showed that the emission of the X-ray can be explained by retarding radiation of nonrelativistic electrons with $\mathcal{E}_k \gg 20$ kev having power energy spectrum $\sim \mathcal{E}_k^{-3}$. In order to explain the observed flux, it is necessary that $N_o(\gg 20 \text{ kev}) = 3\times10^{35}$ electrons. If the spectrum of electrons is extended to the region of relativistic energies, it is possible to satisfactorily explain the observed centimeter radio emission. Thus, the following interpretation of the phenomenon, of flare radiation can be given: hard X-ray radiation originates in the region of a flare or above it as a result of retarding radiation of nonrelativistic electrons being accelerated in the process of development of flares and having, for example, power energy spectrum $\sim \mathcal{E}_k^{-\gamma}$, while the centimeter radio emission of type IV appears simultaneously as a result of synchrotron radiation of these very electrons only if their energy spectrum extends to the region of relativistic energies.

Basic results of observations and investigations by different authors on correlation between centimeter radio emission and X-ray radiation of the Sun are described in Kundu's book [30]. The close correlation between X-ray and radio radiations of $\lambda < 30$ cm and the absence of correlation at $\lambda > 30$ cm indicate the fact that X-ray appear at the same levels as radiation of centimeter waves, i.e., in the chromosphere. It is shown that radiation in X-ray and centimeter ranges can be interpreted as retarding radiation.

The maximum on centimeter waves almost precisely coincides with the maximum for X-rays and sometimes, even conformity in minute details of the two phenomena is observed*. It is assumed that energetic electrons (accelerated in the flare) give rise to outbursts of centimeter radio radiation owing to

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In a report to the International Symposium on Solar Activity (Budapest, September 1967), Arnold et al. reported more than 70 cases of outbursts of hard X-rays with energy 10-50 kev on the basis of observations on "OGO" satellite. On comparing the time variation of these flares with microwave radio outburst ($\lambda = 3$-10 cm), a close similarity between them was observed in the regions of increase and initial decrease of intensity. A similar comparison with the beams of energetic electrons and protons beyond the limits synchrotron mechanism. Invading the lower chromosphere, they give rise to outburst of high-energy X-rays (nonthermal retarding radiation) as a result of collisions with the atoms of neutral hydrogen. Apparently, this conclusion fully supports the conclusion made in the work of A.A. Korchak [IV. 99].

Tanaka and Kakinuma [31] studied the relation between spectrum of weakly-changing components of the solar radio emission and solar proton flares by using interferometric data on wavelengths of 3.2 and 7.5 cm. It was found that most of the solar proton flares during May 1959-December 1961 took place in active regions for which the ratio of the flux densities of radio emission of weakly-changing component at 3.2 and 7.5 cm was more than one. The authors consider that the large value of this ratio indicates the presence of a suitable acceleration mechanism in the active region since the high intensity of magnetic fields of the spots in corona over active regions is one of the conditions of the increase in the value of this ratio. The probability of the occurrence of an outburst of solar protons in the active region, having a high ratio of flux densities of radio emission, is sufficiently high which is important for predicting solar proton flares.

While studying intense radio emission of the Sun on meter bands similar to the short-lived noise storms (from 3 hours to 3 days), L.S. Levitskii [32] showed that it often originates after flares which are accompanied by absorption in the polar cap (i.e., which produce solar cosmic rays).

A solar flare is first of all an explosion and movement of matter and not of energy. Hagen and Barney [33] arrived at this conclusion on the basis of detailed radio-observations on the powerful short-lived flare of June 5, 1965. This complicated phenomenon was recorded by three radiotelescopes of the State University of Pennsylvania at frequencies of 10700, 2700 and 320 MHz. Surplus solar radiation in the beginning appeared at the highest frequency and then at the lowest. Later, 2.2 minutes

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of the Earth's magnetosphere (from the data of satellites 'IMP-1" and 'IMP-3') showed that fast electrons are not observed near the Earth during proton flares (in 7 out of 8 cases) which could have led to outbursts of hard X-rays during their passage through the atmosphere over the Sun's active region.

after the commencement, there took place a radio outburst which was recorded only at the two higher frequencies. Two other flares were observed after 4.8 and 14 minutes. These three frequencies record the activity at altitudes of 10000, 13000 and 30000 km respectively above the solar photosphere. According to [33], the flare was a mass of matter moving externally from the photosphere at a velocity of $>$ 70 km/sec. This matter apparently experienced three explosions during its ascent to altitudes of about 14000, 30000 and, probably, 60000 km.

Works devoted to generation of solar radio outbursts are reviewed in the work of Smerd [34]. The analysis shows that electromagnetic radiation of electrons cannot intensify during collision with ions just like synchrotron radiation. In the case of cyclotron radiation, under certain conditions (positive gradient of distribution function according to energies at the Sth harmonic and insignificant Doppler shift), there will be negative absorption coefficient, i.e., intensification of cyclotron radiation at certain harmonics. Under certain conditions (two-beam unstability), the possible intensification of plasma waves is also observed which later on changes into electromagnetic waves during scattering at thermal irregularities of plasma. The intensification takes place in a narrow band of frequencies near the plasma frequency ($<10^{-3} f_0$). It may be mentioned that the last mechanism is most suitable for explaining the origin of I, II, III types of outbursts: excitation of plasma waves by electron beams of different velocities and their subsequent transformation into electromagnetic waves. This mechanism explains the luminescence temperatures of the order of 10^{11} °K, presence of two harmonics and other characteristic features of this radiation.

A.A. Korchak [35] studied the possible mechanisms of generation of hard X-ray radiation during solar flares. In his work [35], the spectral power of retarding, synchrotron and Compton radiation is compared and the region of X-ray spectrum is determined in which one or the other mechanism can dominate depending upon the physical conditions in the radiation region and the nature of energy spectrum of accelerated particles. If the energy spectrum of accelerated electrons has a power function and continues in the region $\varepsilon_k \leqslant 10^6$ ev with a constant inclination, the retarding radiation will predominate in whole of the X-ray region $\varepsilon_\nu \geqslant 1$ kev.

The relation between proton flares and radio outbursts of type IV is studied by Malville [36]. Since different frequency components of the outburst have different directions, type IV outbursts can significantly differ from flares near the center of the disk and near the limb. The fact, that many flares are not accompanied by outbursts of cosmic rays near the Earth, may be associated with the impossibility of recording weak effects in cosmic rays, error in determination of events in radio range and with the effects of propagation of cosmic rays in the interplanetary medium. The probability of recording cosmic rays after type IV outburst increases if: 1) the intensity of outburst in the range λ = 3-30 cm is sufficiently high; 2) outburst λ = 10 cm attains maximum intensity after the maximum development of the flare in H_{α}; 3) the flare during its development covers a part of the spot. The relation between proton flares and increase in the intensity of yellow coronal line [CaXV] 5694 Å can be explained by assuming the existence of a region of accumulation of accerlated particles in the corona. Magnetic relation between the region of accumulation and the condensation region situated below, leads to the fact that some part of high-energy particles fall in the condensation region and cause its heating. Accumulation region itself is a source of synchrotron radiation observed in the meter range*.

17.3. Peculiarities of flares generating cosmic rays.

Peculiarities of active regions, responsible for solar flares, were studied and data on radio and X-ray radiation of flares were given in an earlier Section. However, it was not possible to record high-energy solar particles in the case of all the flares. In order to solve the problem as to whether cosmic rays are generated in all the cases, it is important to study peculiarities of the flares accompanied by large outbursts of cosmic rays on the Earth as well as to explain the nature of the frequently observed effect of small outbursts of solar cosmic rays (see Section 6).

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* *According to N. P. Tsimakhovich [184], radio emission of flares can serve as an indicator of the chemical composition of cosmic rays. The higher the place of origin of the flare (in corona), the higher will be the flux of nuclei (and lesser will be the flux of protons) and more intense will be the flux of meter radio waves. If the flare occurs deep (in the chromosphere), centimeter radio emission of long duration is observed and there will be significant emission of protons.*

For understanding the peculiarities of flares responsible for the generation of cosmic rays, works of Křivský [37-41] are of great interest. He points out in his works that the generation takes place when two fibers of flare have Y-shaped arrangement The author thinks that this stage can be considered as origin of an open channel along which the accelerated particles come out of the Sun. The Y-phase was detected by Křivský for the flares of November 19, 1949, February 23, 1956, August 31, 1956 [38], July 18, 1961 [39], September 28, 1961 [40] and for many other flares.

The interval between the ejection of cosmic rays from the region of chromospheric flare and their arrival at the Earth is determined in [41]. It is assumed that the moment of ejection of particles coincides with the appearance of Y-phase of the flare which is confirmed by its coincidence with the first maximum of radio outbursts in the centimeter and decimeter ranges. The time of appearance of Y-phase is determined from spectroheliograms and H_α from filtergrams obtained by the author in 1965 at the Crimean Astrophysical Observatory. The time of arrival of particles to the Earth was determined from the commencement of absorption of cosmic radio noise in polar caps and from the increase in the intensity of cosmic radiation based on the data of ground-based equipment.

A catalogue containing data on 13 flares during 1957-61 was compiled. The time between Y-phase of flares and commencement of absorption in polar caps lies within the limits of 10-870 minutes (+ 8 minutes being the time of propagation of light) while the time between Y-phase and commencement of the outburst of cosmic rays varies from 3 to 85 minutes (+ 8 minutes). A part of the catalogue includes corrected and additional data on 16 flares considered earlier [37-40].

Malitson [42] points out that the flares, responsible for the generation of cosmic rays, completely or partially cover the shadow of the main spot and occur in active regions whose life is more than one revolution of the Sun.

A detailed analysis of optical characteristics of flares, emitting cosmic rays, was made by Bruzek [45] during 1959-63. Loop-shaped protuberances were observed in 19 out of 22 events. This conclusion not only gives a suitable optical index of generation of high-energy protons but is also important for understanding the mechanism of flares*.

Guss [44] studied the distribution of flares along heliographic longitude which were accompanied by the effect in cosmic rays. Out of 56 flares recorded during January 1956-October 1962, 13 were observed in the band 80°-90°W and were accompanied by the largest effects in cosmic rays.

By analyzing the data on flares of May 4, November 12 and 15, 1960, McCracken [45] found a correlation between the time of increase in the intensity of solar cosmic rays, degree of anisotropy (or presence of shock zones) and position of corresponding flares on the solar disk. It was shown in the work that the flares on the western limb give strongly collimated particles with quickly increasing intensity while flares in the center or on the eastern edge of solar disk give weakly collimated or even isotropic beams of particles.

It is known that large outbursts of the intensity of solar cosmic rays have the tendency to appear during the years of the decrease or increase of solar activity but not at the time of maximum cycle. An analysis of the dependence of the frequency of flares on their amplitude A is reported in the work of A. I. Kuz'min and G. F. Krymskii [IV 74]. It is shown that the integral spectrum of the frequency of flares, recorded by neutron monitors, has the form $N(\geq A) \sim A^{-\alpha}$ where $\alpha = 0.5$-0.6. It is mentioned that this point of view is shared by many research workers, and the effect is explained by the existence of conditions most favorable for the propagation of solar particles in the interplanetary space during this period. Takakura and Ono [46] put forward another hypothesis for explaining this tendency. They suggest that the frequency of the appearance of class 3^+ flares is constant during about three years after the maximum solar activity while the frequency of other flares during this

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[*] *It was mentioned in the report of Z. Shvestki at the International Symposium on Solar Activity (Budapest, September 1967) that proton flares are always accompanied by loop-shaped protuberances. A. B. Severnyi at the same symposium submitted data showing that the region of a proton flare corresponds to places of largest currents calculated from the vector of the magnetic field.*

period decreases very sharply. On the other hand, the most intensive radio outbursts of type IV, accompanying the generation of fast particles, have a tendency to appear during the phases of rise and fall of solar activity. If it is considered that class 3^+ flares, accompanied by intense radio emission of type IV (as compared to class 3^+ flares not accompanied by such radio emission) are more effective for emission of solar cosmic rays, it is possible to formulate the following model [46].

If the cosmic rays are to be ejected, firstly, constant accumulation of magnetic pressure due to gradual twisting of magnetic field is necessary and secondly, there must be some starting mechanism which may release the accumulated magnetic energy. In that case, at the time of maximum activity, a large number of disturbances should be observed in the solar atmosphere because of this starting mechanism and thus, the interval between disturbances will be very small so as to accmulate large energy required for accelerating the particles. At the same time, the number of disturbances, which could start ejection of particles, during the ascending and descending phases of solar cycle should be moderate. On the basis of this, the authors [46] assume that the decrease in the intensity of cosmic rays at maximum solar activity is a solar effect rather than a modulation effect.

Vogt [47] showed that there are beams of low-energy protons in primary radiation even during the period of maximum solar activity. An increase in the flux of low-energy protons, caused by the arrival of particles from September 3, 1960 flare, was detected on the basis of data obtained on balloons over Churchill. It is assumed that such protons are also injected in the interplanetary space during chromospheric flares. The effect of small flares of cosmic rays was discussed in a number of works of L.I. Dorman et al. (see Chapter II).

The results of statistical analysis of increases in the intensity of cosmic rays are given in the work of Yoshida [48] who, on the basis of data of 21 stations during July 1957-December 1960, detected that this effect is related to meter-band outbursts of radio emission of type IV. At the same time, decimeter-range radio outbursts of type IV are not related to any increase in the flux of cosmic rays. Following are the peculiarities of statistical outbursts observed in [48]: 1) magnetic cut-off according to rigidities is same for statistical increase and unusual outburst only if they are recorded a few hours after solar flare; 2) distribution of particles is isotropic; 3) time lag between flare and isotropic statistical outburst is 8-18 hours.

Kodama [49] divided the observed flares into 4 types according to the nature of outburst effect: 1) unusual outbursts of cosmic rays (more than 100% on the Earth's surface); 2) small increases (0.1-1%) and polar absorptions; 3) quick increase (delay with respect to radio outbursts of type IV less than 6 hours); 4) slow increase (delay more than 6 hours).

Peculiarities of active regions, generating solar cosmic rays, were studied by Noyes [50] on the basis of the data of observations during the period July 1957-December 1960. Out of the 40 events of recording solar protons during this period, 30 can be definitely related to 20 active regions (a few events of generation of cosmic rays are related to the same active regions). These regions, representing the most active ones, on an average, are mainly characterized by magnetic configuration of sunspots of type $\beta\gamma$ or γ, area of sunspots $> 2 \times 10^{-4}$ part of the solar hemisphere and by the presence of five or more flares of class 2. On an average, more than 60% of the flares during these periods, giving rise to polar absorptions and outbursts of the intensity of cosmic rays, were observed: 1) in the northern hemisphere of the Sun; 2) towards west of the central meridian and 3) during first or second revolution of the given active region.

The problem of the differences between chromospheric flares, accompanied by the increases in the intensity of cosmic rays, and ineffective flares is very important. A thorough analysis of this problem, by taking into account all the possible characteristics of flares, shows that there are very significant differences. Ellison et al. [2] summarized the characteristics of 6 flares (February 23, 1956, May 10 and July 16, 1959, May 4, 1960, November 12 and 15, 1960) which gave rise to increases in the intensity of cosmic rays on the Earth's surface. These flares were distinguished by bright radiation in H_α which lasted for 2-3 minutes, large area of about 2000×10^{-6} part of the hemisphere, presence of twin bright fibers intersecting the group of spots and going parallel to the magnetic axis, and by the covering of the shadow by fields of maximum intensity. During the last five events, continuous radio emission of type IV of large intensity and duration was recorded while sudden cosmic noise absorptions were recorded during all the events. Heliocoordinates of these flares show significant asymmetry which is absent in the case of normal flares of class 3 and 3^+. There exists noticeable predominance of flares situated towards west of the central meridian and five events were observed when the flares took place near the western edge of the disk. It shows that high-energy particles, accelerated during flares on the western side of the disk, reach the Earth easily and along less-distorted paths. From this it follows that the presence of radial magnetic fields in the space between the Sun and the Earth are slightly distorted as a result of twisting of lines of force towards west due to rotation of the Sun. All the flares, excepting one (whose heliolongitude was 2°S) were observed in the north of the solar equator. It can mean that the radial fields get inclined towards south (it might be related to motion of the Sun in the direction of solar apex). Some of the flares under reference belong to the category of the biggest flares ever observed while other flares are not distinguished by high intensity of optical characteristics. Ellison et al. [2] draw the conclusion that arrival of high-energy particles, which can give rise to effects in cosmic rays on the Earth's surface, is mainly determined not by the optical intensity of the flare but by such factors as non-constancy of magnetic fields in the space between the Sun and the Earth, location of flare on the solar disk and nature of magnetic field in the group of sunspots.

With the aim of exposing the peculiarities of flares generating powerful beams of fast particles, Athay [51] thoroughly studied the phenomena associated with large flares of cosmic rays on July 16, 1959 and on November 12, 1960. These phenomena are compared by him with the conditions on the Sun during the periods July 6-22, 1959 and November 5-21, 1960. The comparison of characteristics of optical and radio emissions of large chromospheric flares shows that there is no significant difference between the flares responsible for large increases in the intensity of cosmic rays and having no noticeable outbursts. The author mentions that although any such type of differences have not been detected up to this time, it is necessary to search for them. Discussion of observational data on magnetic fields and different types of radiations lead the author to the conclusion that the usual concepts on flares can be wrong and that huge liberation of energy is the most important peculiarity of flares giving rise to large beams of solar cosmic rays*.

17.4 Relation of the amplitude and time variation of solar particles with the characteristics of chromospheric flares, Forbush effects and geomagnetic storms. Interesting results on the nature of propagation of solar cosmic rays were obtained by Yoshida and Akasofu [II. 42] who grouped together the Forbush effects (according to amplitude of decrease in cosmic rays) and geomagnetic storms (according to characteristics K_p and D_{st}) depending on the peculiarities of solar cosmic rays generated by the same chromospheric flares that were responsible for geomagnetic storms. It was shown that a significant difference in the appearances of flares on the Earth, depending upon their heliologitude, is observed only on grouping in this manner. It was also shown that chromospheric flares, giving rise to noticeable increases in the intensity of cosmic rays, lead to the release of an huge amount of energy resulting in geomagnetic storms and to large Forbush reductions.

Variations in the intensity of neutron component of cosmic rays have been studied by V. I. Ivanov et al. [52] on the basis of the data of world network of stations during chromospheric flares accompanied by electromagnetic radiation and during 15 intensifications in the brightness of the Sun which were accompanied by X-ray radiation (A. K. Pankratov [53]) during the period of maximum solar activity. By the superposed epoch method it was found that the increase in intensity in the shock zones is equal to 0.25% while the amplitude of increase outside these zones is of the order of 0.1%. These results once again confirm that cosmic rays can be generated on the Sun even during less-active processes which are accompanied by electromagnetic

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**On the whole, one has to state that a specific criterion, which could unambiguously characterize a proton flare, has been found neither in the optical nor in the radio range of the Sun.*

radiation [II. 19; II. 22; II. 23]. It was also shown in the work [52] that the amplitude of outburst in shock zones decreases with the decrease in solar activity while the rate of decrease of intensity increases. The duration of decrease from eastern flares changes less than that from western flares and the change in the duration of decrease depends more strongly on heliolongitude than on heliolatitude. The rate of increase for eastern flares is less than that for western flares and the maximum of intensity is diffused. The ratio of the effects from flares on western hemisphere of the solar disk to the effects from flares on the eastern hemisphere is less during the years of minimum solar activity.

In recent years, the attention of many research workers was attracted by the continuous optical radiation of chromospheric flares (see, for example, the works of McCracken [54], Becker [55], de Yager [56], Michard [57]). The observational data on these "white" flares is still scanty but nevertheless analysis of this problem by Yu. N. Dolginova and A. A. Korchak* showed that the white flares do not at all differ from the usual flares (including those which are accompanied by propagation of high-energy particles to the Earth). This conclusion ~~confirms~~ the assumption made by the authors [55-57]**.

B. M. Vladimirskii and A. A. Stepanyan [59] paid much attention to the fact that half of the large outbursts of solar cosmic rays took place during Forbush effects (March 2, 1942, August 31, 1956, July 16, 1959, May 4, 1960, November 3, 1960,

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* *Personal communication.*

** *It is interesting to mention that the May 23, 1967 flare of class 3, according to observations at Boulder [58], was brighter in white light than the surrounding photosphere by a few percent. Polarization of radiation in white light was not observed. According to the observations at the Sacrmento-peak Observatory, the maximum in white light for this flare was recorded at 1840 UT while according to photographs in H_α, the maximum occurred at 1844 UT. The flare was accompanied by a powerful magnetic storm, polar aurora (May 25), intensification of X-ray and radio emissions and by the increase in the flux of low-energy solar cosmic rays.*

At the International Symposium on Solar Activity (Budapest, September 1967), Newcrick et al reported data on the fact that an increase in the intensity of white corona is observed during a proton flare. The region of this illumination is much more than the area of flare in chromosphere.

November 12, 15 and 20, 1960, July 18 and 20, 1961, etc). About 50% of polar absorptions were also observed during Forbush effects. Here, in most of the cases, chromospheric flares giving rise to outbursts are situated in those very active regions which are responsible for Forbush reductions. A detailed statistical analysis was done in [59] by the method of superposed epochs of flare effects (class 2 and 3) during six Forbush reductions on the basis of the observational data on the neutron component of cosmic rays obtained by the world network of stations (see Table 17.1).

According to [59], it follows from the experimental data that if the flares occur in the region responsible for Forbush effect, solar cosmic rays reach the Earth earlier and their beam is more anisotropic (there are shock zones) than in the case when chromospheric flares occur in some other active region.

Let us review some more works in which the questions related to properties of flares and their geophysical effects are considered.

While analyzing heliolongitudinal distribution of flares, Warwick [60] showed that the proton flares which gave rise to intense polar absorption have a more distinct tendency to appear at certain preferred heliographic longitudes than appearing near the spots and other active regions of solar formations. The diagram, illustrates the concentration of proton flares during 1954-63 at heliolongitudes of 140° and 320°, and 2 active antipodal longitudinal intervals. Locations of proton flares are related to a rigidly rotating layer of the Sun. It is reported that the longitude intervals, where proton flares usually occur, coincide with those of huge concentrations of visible, active, solar formations.

Characteristic features of the distribution according to heliolongitudes of: (a) flares after which solar cosmic rays were detected only from absorption of cosmic radio noise in the Earth's polar regions and (b) flares after which cosmic rays were recorded at sea level are discussed in the work of Křivský [61]. A three-dimensional model of the cloud of solar cosmic and subcosmic particles has been suggested on the basis of these characteristic features. Half width of the cloud in the

TABLE 17.1

Forbush reduction				Effects of flares in the active region			
				responsible for Forbush reduction		not leading to Forbush reduction	
Time of commencement of flare	Helio-coordinates of the flare responsible for Forbush reduction	Amplitude of reduction, %	Duration, hrs	no. of flares	average amplitude of outburst, %	no. of flare	average amplitude of outbursts, %
August 29, 1957	31°S, 33°E	9.0	-	3	0.34	1	0.3
Sept. 29, 1957	22°N, 15°E	5.2	157	2	-	1	0.3
Oct. 21, 1957	26°S, 45°W	9.6	406	-	-	2	0.24
Nov. 26, 1957	14°S, 37°E	6.3	158	-	-	3	0.17
March 25, 1958	14°S, 78°E	7.9	366	6	0.29	9	-
Sept. 16, 1958	10°S, 80°W	4.5	326	-	-	10	-

eclipitic plane at the Earth's orbit is of the order of 45-110°. The axis of the cloud at the Earth's orbit is inclined in the eastern direction at an angle of 40-80° from the radial direction in the flare region.

Mentioning the significance of the problem of prediction of chromospheric flares, accompanied by ejection of particles of solar cosmic rays (proton flares), A. S. Dvoryashin [62] describes following characteristics associated with them: 1) the strongest effects in the polar ionosphere correspond to radio outbursts of type IV with the predominance, in terms of power, of the first phase (in the centimeter range); 2) X-ray radiation of proton flares is characterized by long duration, wide interval of wavelengths and presence of photons of energies right up to 0.1 Mev (which is detected from ionsopheric effect at those observation points where the Sun at the time of the flare was in the horizon). The problem of the geometry of interplanetary magnetic field is briefly discussed on the basis of work of the author on the analysis of the data on minimum reflection frequencies (f_{min}).

A very important result was obtained by M. N. Gnevyshev and L. Křivský [63] who showed that the number of protons as well as the number of chromospheric flares in the 11-year cycle have two maxima in the same way as the intensity of corona, number of protuberances, area of sunspots and intensity of radio emission of the Sun. The proton flares appear at the places of intense brightness of the corona. The second maximum is characterized by the appearance of extremely strong phenomena, for example, flares of solar cosmic rays. A catalogue of proton flares during 1954-1964 is given in [63]*.

Before this Section ends, let us mention some of the reviews summarizing the results of investigations on flares conducted during the past few years. V. G. Banin [64] analyzed in detail the problem of magnetic fields in powerful chromospheric flares. In particular, the following basic problems of the physics of solar flares are enumerated in the review of Glaser [65]: explanation of the mechanism of accumulation and quick liberation of huge amount of energy (10^{32} erg) during 1000-2000 seconds; search for the mechanism of acceleration of solar cosmic rays to 1 Gev; causes as to why some flares are not accompanied by radio emission while in other cases, radio emission is observed without visible solar flares. Much attention is paid to the red fluorescence on the Moon's surface, and to two recorded cases which are assumed to have been observed after two solar flares (see Section 12.1).

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* *Sakurai [104] found that during the descending phase of the cycle of solar activity (1959-1963), proton flares most frequently occurred only in two regions in the northern hemisphere of the Sun. These two active zones, separated by 160° along the longitude, coincide with the regions of strong brightening of the green coronal line where strong magnetic fields are supposed to be existing.*

Smith [66] gave a detailed review of the structure, development and the motion of flares. Analyzing the distribution of flares according to latitude and longitude, the author [66] arrives at the conclusion that flares are not plane formations but have certain height. The east-west asymmetry is apparently absent. Number of flares as well as probability of the appearance of strong flares is more in long-life centers of activity. In small groups of spots existing for less than 3 days, flares are rare or are absolutely absent. The dependence of the number of flares on the number of spots is very weak. Flares on an average appear every 20-30 minutes near the maximum of sunspots. The relation between the area and duration of a flare is very weak. Flares are slow-moving formations: their velocity along the vertical is up to 10 km/sec but their tangential velocities, determined from the Doppler effect, sometimes go up to 200 km/sec. Disturbances due to a flare, especially due to an explosive one, are spread at a velocity of the order of a few hundred km/sec. The so-called homologous flares have a strong tendency to reappear at almost the same places in the active region. The other class, i.e., coordinated flares are characterized by the fact that they are caused by a previous flare. The excitation in these cases propagates at a velocity of about 1000 km/sec. On the limb, the flares have the form of circular suspensions, cone, loop or irregular structure. Most of them attain a height of 2000-10000 km while the average height is of the order of 7000 km and the maximum height, 50000 km. The relation between the intensity of H_α line and the area of a flare at maximum brightness is very weak. Extremely strong flares have a brightness about 25 times that of the quiet chromosphere. Many flares are accompanied by ejections of a gas. Propagation velocity of ejections of the surge type varies from 50 to 200 km/sec and that of sprays goes up to 1500 km/sec.

A number of effects caused by flares (absorption of short radio waves, Forbush decrease of cosmic rays and other phenomena in the Earth's surroundings) are considered in Chapter II (also see the reviews of Byrne et al. [67], Elliot [68] and Roederer [I. 90]).

18. THEORETICAL INTERPRETATION OF PHENOMENA IN SOLAR FLARES

Earliest attempts on the interpretation of the processes of solar flares were based on the discharge theory. The essence of this theory lies in the fact that electrons in the presence of an electric field attain additional energy. On increasing the temperature of electrons T_e, the frequency of their collisions with ions decreases; the losses of energy also decrease and this leads to further increase in the energy of electrons. Since conductivity $\sigma \sim T_e^{3/2}$, a process similar to a discharge takes place. The interpretation of the flare as the result of an electric discharge taking place just near the neutral point of the magnetic field, was assumed by Giovanelli [69] and was later developed by Dangey [70]. While commenting on the discharge theory of flares Cowling [71] and afterwards, A.B. Severnyi [3] showed that strong electric fields, under the conditions of a flare, cannot exist due to high conductivity of plasma.

On the other hand, Ellison [72] found the value for energy, emitted by solar flares, to be of the order of 10^{32} ergs. It gives a yield of about 10^3 erg/cm^3 which is about 10^3 times the density of thermal energy in an equivalent nonflare region. This fact necessitates introduction of magnetic field in the theory of flares since only magnetic field can accumulate the required energy.

Let us briefly consider some of the models of accumulation and subsequent rapid release of energy of particles due to magnetic field.

Wentzel [73] considers the rapid collapse of unstable chromospheric region to a region of the minimum but finite intensity of field under the action of magnetic forces as a possible mechanism of a flare. The process of formation of a flare starts from the development of magnetohydrodynamic turbulency during the collapse. Compression of magnetic field leads to a break in the collapse (moment of maximum flare) since plasma luminescence gets intensified during collapse because of ohmic dissipation of energy in the case of a collision of "magnetic whirls" with the lines of force in the opposite direction. Turbulence and luminescence start fading after the break in the collapse.

If the collapse develops in the higher layers of the Sun's atmosphere where density is low, the dissipated energy of the field will not be carried away by radiation but will only heat the plasma. In this case, in place of a chromosopheric flare, there can be a "corona" outburst accompanied by X-ray, corpuscular and radio emissions. Under reasonable assumptions about the dimensions of "whirls", the model gives values which are in agreement with observations: duration of flare 35 minutes; total thickness of emission layer 4.5 km in the case of a flare of size $5x10^3$ km; electron concentration 10^{12}-10^{13} cm^{-3}.

The nature of the brightness curve, appearance of dual and simultaneous flares as well as some other characteristic features of flares can be explained qualitatively on the basis of the suggested explain the peculiarities of the acceleration of solar particles in flares with the help of this mechanism.

In the earlier work of Gold and Hoyle [74], the twisting of solar magnetic fields is taken as the basis for formulation of a model of flares. It is assumed that this process, described by Babcock, envelopes photosphere as well as chromosphere by keeping a large amount of energy as surplus. Here, to initiate the flare, a starting mechanism is thought of, which requires another magnetic loop and twisting in the opposite direction. As shown in the review of Byrne et al. [67], this theory does not explain the observed double threads of luminescence during flares; moreover, the assumed starting mechanism requires fulfillment of extremely complicated conditions.

Jacobsen and Carlqvist [76] describe the similarity between solar flares and voltage surges appearing at low pressure in a discharge tube connected to an inductance circuit. It is assumed that the current system in chromosphere represents fibers which connect different parts of spot groups and pass through the corona. Existence of such current systems corresponds to accumulation of energy in magnetic fields associated with them. In this case, characteristic conditions of plasma are retained; the voltage drop of the electric field along the fiber is small. If neutrality of charge is locally disturbed due to some reason, voltage drop at this place increases abruptly. A double electric layer is formed, a part of the accumulated energy changes into the energy of space charges and the particles get accelerated accompanied by rapid liberation of energy. The author shows that in order to fulfil the necessary conditions, it is sufficient that the current, passing through the boundary between chromosphere and corona, may be more than some critical value.

The dynamics of magnetized plasma was studied in a number of works by A.G. Severnyi [3, 77, 78] in connection with the problem of solar flares. He suggested the following model of flares. As a result of typical hydrodynamic motion of the lines of force and as a result of the growth of the field of spots, there originates a neutral point with a strong gradient of field around it and the plasma gets rapidly compressed (during a few seconds) around the central point which develops at an ever-increasing velocity. The compression is stopped by the developing shock wave at a distance $\lesssim 10$ km near the neutral point. The plasma in this volume attains a temperature of about 5×10^6 °K The remaining, large part of the flare beyond the front of the shock wave gets widened. Thus, the flares were considered as a type of pinch effect, i.e., self-compression of plasma around the neutral axis, appearing as a result of unstability of plasma. Here, it was assumed that dynamics of this one-dimensional process is defined by the rapid growth of magnetic pressure of the plasma as compared to the gas pressure.

This model was analyzed in detail in the work [77] in which the causes of the origin of self-compression were studied. It was shown that the "starting mechanism" i.e., the magnetic field, during rearrangement of which the energy of the plasma retained in the field gets liberated, is switched-on after the exit on the Sun's surface and subsequent closing of magnetic toroids having opposite direction of the lines of force. If the toroids are stable, there must exist azimuthal fields around them which at the places of contact have opposite directions. These fields quickly destroy each other at the places of contact. A similar situation arises either during self-closing of the tube if the tube during bending undergoes twisting leading to the origin of azimuthal fields or during contact of two tubes of force similar to traps. In the latter case, external pressure up to the time of contact is balanced by the sum of magnetic and gas pressures inside the tube but when the field at the place of contact is destroyed, the magnetic pressure reduces sharply and the force of external pressure starts acting on both the tubes. This force tries to compress them relative to the neutral plane, i.e, there takes place the process equivalent to rapid withdrawal of a part of plasma from the region of contact.

While developing the model of self-compression of plasma around the neutral points of magnetic field-- the model which was earlier discussed in [77]-- V.P.Shabanskii [79] showed that, in this case, the observed magnetic fields and their gradients in the regions of neutral points must coincide with the current flowing in the same region. In this case, it is difficult to think of the conditions for realizing the mechanism of self-compression since this mechanism does not leave any place for the possibility of slow accumulation of energy owing to the fact that a mechanism, hindering the compression before some fixed time, has not been forseen in this model. V.P.Shabanskii studies in detail the possibility of the appearance of a similar state in the case of amalgamation of two tubes of forceless fields into one tube in which two azimuthal fields will exist in opposite directions. Under favorable conditions, the time of diffusion of internal longitudinal field into plasma can be of the order of 10^3 seconds. Annihilation of these fields releases the pressure of longitudinal field counteracting the compression. The whole of the configuration starts getting compressed under the action of the azimuthal field while the inside region will get heated. It is suggested that the process of annihilation of fields takes place not in the chromosphere (in the region of flare) but at large depths where concentration of particles is of the order of 10^{17} cm^{-3} and pressure of gas is comparable to the pressure of magnetic field. In this case, energy liberated during annihilation of the field is low as compared to the thermal energy of the plasma and does not lead to significant heating of this region. It facilitates to retain favorable conditions for cross diffusion of oppositely directed azimuthal fields. In the case of such a process in the chromosphere, heating can freeze the fields and stop the process. In the case of transfer of reorganizing magnetic fields into the chromosphere, this process will have the nature of a flare.

As far as the latter mechanism is considered, recently Kopecky [80] showed that it is necessary to reconsider the existing view on the mechanism of formation of spots as a result of lifting of magnetic tubes from deep layers in the photosphere and to find a new mechanism of formation of spots and fields, associated with them. This conclusion has been drawn on the basis of investigation on the theory of disintegration of magnetic fields of sunspots which was put forward by Künzel et al. [81]. According to this theory, the time of disintegration of spots is comparable to the duration of the existence of spots. It contradicts Cowlings theory which gives disintegration time more by a few orders.

Basic aspects of A.B. Severnyi's theory were criticized by S.I. Syrovatskii [82]. First of all, S.I. Syrovatskii showed that the dynamics of the process of compression, defined in [77] by the growth of magnetic and gas pressures, actually depends on the gradients of these parameters. Afterwards, on the basis of the solution of the system of magnetohydrodynamic equations for the case of small disturbances, he showed that one-dimensional compression leads either to a new state of magnetohydrodynamic equilibrium or, on considering nonabaticity of compression, pointed out by A.B. Severnyi [83], to compression with a velocity determined by the rate of transfer of heat from the system. Thus, on the basis of A.B. Severnyi's model, it is difficult to expect some quick processes of rearrangement and dissipation of magnetic fields.

Unstable nature of plasma at the time of origin of solar flares was also discussed by Jaggi [84]. He analyzed magnetohydrodynamic unstability of plasma of conductivity $\sigma = \infty$. This unstability is related to the gradient of magnetic field in the region of neutral points of the magnetic field near the spots. After pointing out the principal difference of laboratory pinch effect from the conditions in chromosphere in the region of neutral points and by using the method of analyzing plasma stability of relatively small disturbances, Jaggi found that plasma with $\sigma = \infty$ is stable in the region of neutral point. Possibly, gradients of magnetic field in the region of neutral point are such that unstability practically cannot develop. The time of development of unstability for long-wave disturbances (of the order of Larmorov radius of electron) was estimated to be 10^{12} seconds.

The problem of the origin of plasma unstability in the region of neutral points is considered separately for the case when isotropic plasma conductivity is finite. In this case, two types of unstabilities are possible: fluctuating and explosive. The time of growth of explosive unstability in the case of long-wave disturbances has been evaluated at different values of temperature and magnetic field in the chromospheric plasma. This time lies within the limits from a few seconds to a few minutes which corresponds to the time of development of a chromospheric flare.

A brief review of works, interpreting a flare as an explosive phenomenon, was made by R. Kh.Guseinov [85].

The model of the origin of a flare in the neutral plane between two dipolar fields, suggested by Wild [86], is of some interest.

Out of a large number of theoretical mechanisms taking up annihilation of magnetic field for explaining processes of flares at present the most prospective are the theories which consider rapid rearrangement and dissipation of magnetic fields into the class of two-dimensional flows.

The first step in this direction was taken by Sweet [87] who studied one-dimensional steady compression of plasma between two antiparallel layers by considering outflow of plasma in the radial direction along the layer. Sweet showed that, if the gas pressure is less than the limiting value, hydrostatic equilibrium in this case becomes unstable in the conducting medium. Motion, caused by disturbance of hydrostatic equilibrium, leads to the fact that the distance between oppositely directed lines of force will be reduced and a velocity of dissipation, sufficient for accelerating solar particles, can be obtained in this way.

However, while quantitatively evaluating Sweet's model, Parker [88] afterwards showed that it leads to extremely large durations, necessary for releasing the energy. In order to get lesser time of dissipation of magnetic field than the one obtained from Sweet's mechanism, Parker included the mechanism of ambipolar diffusion in Sweet's model. The essence of this mechanism lies in the fact that the magnetic field moves along with the electrically-conducting ionized component of plasma whose motion relative to the neutral component is delayed by friction caused by the collision of ions with neutral atoms. Owing to this phenomenon, decrease in effective conductivity can be included in the value of velocity of dissipation of magnetic field.

While reconsidering the mechanism of Sweet and Parker, Petchek [89] showed that the time necessary for conversion of magnetic energy into thermal energy is very large even on considering the mechanism of ambipolar diffusion suggested by Parker. The mechanism of propagation of magnetohydrodynamic waves will play an important role since ambipolar diffusion decreases on increasing conductivity. It is pointed out in the work of Petchek [89] that in the case of a stable beam, both the mechanisms i.e., diffusion as well as propagation of magnetohydrodynamic waves, function simultaneously leading to a higher velocity of annihilation and rearrangement of magnetic lines of force in the medium of high conductivity as compared to the case when the wave mechanism is not taken into consideration. According to Petchek's estimate, in the case of a compressible beam corresponding to solar flares, the energy, required for a solar flare, can be released during 10^2 seconds.

Thus, this theory satisfactorily explains the rapid heating and ejection of plasma in the region of solar flares. However, the question of the generation of accelerated-particles remains unanswered in this theory.

The model suggested by S.I. Syrovatskii [90] gives the most rigid picture of rapid dissipation of magnetic field providing effective acceleration of charged particles. By solving the magnetohydrodynamic equations for two-dimensional motions of plasma in the fields where the condition

$$p \ll \frac{H^2}{8\pi}, \qquad (18.1)$$

is satisfied, S.I. Syrovatskii obtained the equation of motion of plasma in the form

$$\frac{dv}{dt} = -\frac{1}{4\pi\rho}\Delta A \nabla A, \qquad (18.2)$$

where p and ρ are gas pressure and density of plasma respectively and A is the potential vector of the magnetic field, It is shown that, in this case, the disturbance of the initial equilibrium state leads to quick (with Alfven velocity v_A) establishment of a new quasiequilibrium state by displacing the transverse lines of force; moreover, the system will undergo a number of quasiequilibrium states determined by condition of equation (18.1).

By studying this problem for the region with neutral point, appearing between two parallel currents situated on x-axis and displaced to a small distance δ, it is possible to get the picture of motion of plasma and the frozen magnetic field which is shown in Fig. 18.1. As is obvious from the calculation of Jacobian transition from undisplaced coordinates to displaced ones, there appear regions with strong evacuation and compression of plasma during the process of displacement in the region $r \gg r_s$ (r_s is the distance at which Alfven velocity becomes equal to the velocity of sound).

In the region $x \lesssim \sqrt{\delta}$ there also appears a region of strong compression in which the characteristic ratio of the gradient of field to the concentration of plasma is equal to

$$\frac{h}{n} \sim \frac{h_0}{n_0}\frac{\delta^2}{r_s^4}, \qquad (18.3)$$

where h is the gradient of the magnetic field.

This value determines the criteria of violation of frozenness in this region since owing to quasi-stationary equation

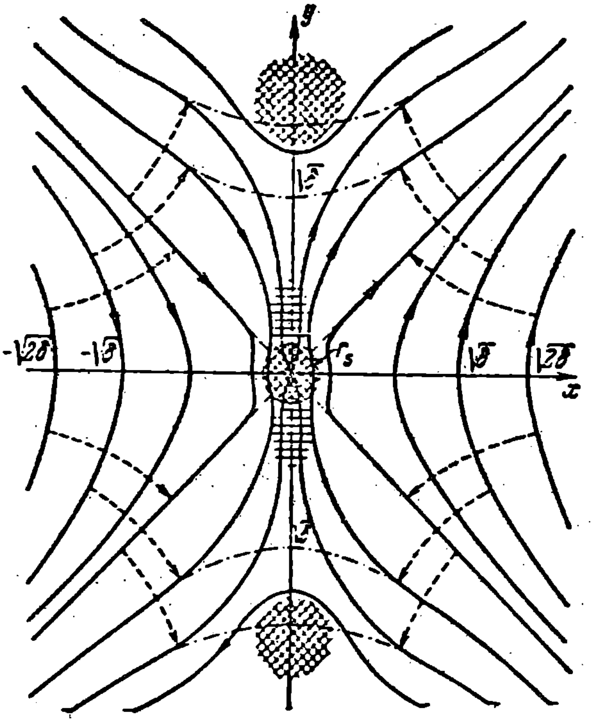

Fig. 18.1. Qualitative picture of deformation of magnetic field in the model of dynamic dissipation [90]. Horizontal hatching-region of evacuation; double hatching - region of strong compression. Dotted arrows show the direction of deformation of the field.

$$\operatorname{rot} \mathbf{H} = \frac{4\pi}{c} \mathbf{j} = \frac{4\pi}{c} \sum_i n_i e v c$$

the ratio h/n cannot go beyond the obvious limit

$$h/n < 4\pi e, \tag{18.4}$$

where n is the concentration of charges of both signs in the plasma.

If the condition (18.4) is not satisfied, it means that the concentration of charges is insufficient to balance the increasing gradient of the magnetic field. It leads to the production of an induction electric field E which, as if directed along the current $\mathbf{j}$, accomplishes positive work on particles by increasing their energy; this is the process which provides transformation of magnetic energy into kinetic energy of particles, i.e., dynamic dissipation of magnetic field. It is characteristic that this process is not associated with Joule dissipation and if the condition of frozenness is not satisfied, current density becomes maximum and the energy of the field is spent on increasing the total (relativistic) energy of particles.

$$\varepsilon = \sqrt{c^2 p^2 + m_0^2 c^4}. \tag{18.5}$$

From the estimate of energy concentrated in the region of magnetic compression

$$W_{\text{м}} \sim \frac{1}{8} h_0^2 \delta^2 \tag{18.6}$$

it follows that a fraction δ of the total energy released is concentrated in the region of compression. The remaining part is spent on compression in the region $y \sim \sqrt{2\delta}$ and on deformation of the field in the surrounding atmosphere.

Time characteristics of the process are determined from the relation between fall of pressure in the region under reference and the gaseous dynamic motion of plasma balancing the fall of pressure. It is shown in [90] that the influx of plasma cannot balance the fall of pressure if the basic currents move with a velocity $v \gg s\sqrt{\delta}$ where s is the velocity of sound in plasma.

Since the motion in the region of strong field takes place with Alfven velocity $v_A \gg s$ this process can be realized in practice.

The obtained results were applied by the author to the phenomena taking place in a solar flare. Characteristic time of the process at the usual values of concentration, temperature and gradient of the magnetic field was found to be $\tau \ll 3 \times 10^2$ sec. It was shown that only fast magnetic electrons are easily generated in active regions on the Sun: strong gradients and significant displacements of spots are necessary for flares generating relativistic particles. It was found that the liberated energy is of the order of 10^3 ergs, number of accelerated particles $N \sim 10^{34}$ and their average energy $\mathcal{E} = W_M / N \sim 10^9$ ev.

S. I. Syrovatskii assumes that the regions of strong compression and flow of plasma along the line of force can be responsible for optical radiation of flares and for the phenomenon of loop-shaped protuberances.

This model does not explain a number of questions such as subsequent progress of the process, distribution of accelerated particles according to energies and charges, etc. Nevertheless, S. I. Syrovatskii's conclusion about the appearance, in unstable plasma, of the regions with strong compression and at the same time, with high vacuum, which is the cause of generation of fast particles, is very important for understanding a number of questions of magnetic hydrodynamics and physics of cosmic rays.

The problem of the stability of plasma in the region of sunspots is considered in a number of works. In particular, Sweet [91] analyzes the stability of twisted plasma-tube with forceless magnetic field as applicable to the problem of the nature of chromospheric flares. Axially-symmetrical forceless field becomes unstable at a particular critical value of the variable parameter $\alpha = \alpha_{crit}$ in the relation rot H = α H. The problem of stabilization of two-axial configuration of the field has been studied with the help of the current layer. In the case of finite conductivity of plasma, the surface current layers will intersect the asymptotic lines of the magnetic field. Energy aspect of dynamic stability of forceless magnetic fields with asymptotic lines has been studied for the case of ohmic dissipation. The parameter of the forceless field changes due to dissipation processes and due to transformation of internal magnetic flux into external "current shell". The energy diagram of forceless field is given which facilitates qualitative determination of the behavior of the critical value of the parameter α_{crit} at which there appears unstability and annihilation of field, determining the energy of chromospheric flare.

Stability of magnetic fields of sunspots is studied theoretically in the work of Sakurai [92]. Although, in general, they are unstable, solar plasma, surrounding the tubes of force, has a stabilizing effect. In the case of any change in this equilibrium in the lower part of the tube of force floating in the chromosphere in lower corona, unstability develops rapidly and leads to sudden collapse of the field and to rapid compression of the lines of force. The plasma in the tubes gets heated while the part of plasma with superthermal velocity gets accelerated to the energies of cosmic rays and thus, becomes the source of solar cosmic rays and electrons of high energy. Electrons are retained near the flare by magnetic fields and while interacting with the fields, they become a source of radio emission of type IV. A part of the accelerated electrons which had penetrated into the chromosphere, after getting scattered at hydrogen atoms, ions and irregularities of magnetic field, pass through the corona accompanied by radio outbursts of type III. Braking radiation during scattering of these electrons is identified as outbursts of X-ray radiation. Immediately after plasma heating, there takes place widening and floatation of magnetic fields beyond the limits of the flare region followed by generation of shock wave which excites radio outbursts of type II. During the upward motion of field along with plasma, an electron cloud is formed which acts as flare nimbus and loop-shaped protuberances responsible for radio outbursts of type IV_m B. The author emphasizes upon the fact that chromospheric flares as well as acceleration mechanism of particles are closely related to the unstability of the configuration of magnetic fields in the group of sunspots.

A general physical picture of solar flares, which is related to changes in magnetic fields of sunspots is suggested in another work of Sakurai [93]. It is mentioned that two fundamental processes -- compression and widening of two mutually interacting magnetic tubes -- form the base of these changes. Two phases of a flare corresponding to these processes are pointed out. A list of phenomena associated with each of the phases, is given in the article in the form of a table. It is mentioned that the phenomena, corresponding to the compression phase, point out the important role of this process in the generation of high-energy particles. The phenomena, accompanying the expansion phase, are important for understanding the exit of particles and waves, generated during the flare, in the interplanetary space.

The role of electric fields in accelerating particles during flares was studied in detail by Sakurai [94].

19. CHARACTERISTIC FEATURES OF THE SPECTRUM AND COMPOSITION OF SOLAR PARTICLES AND ACCELERATION MECHANISMS

Flux of solar particles is measured in three proximate (or overlapping) energy ranges: 1-50 Mev (riometers, rockets and satellites), 50-500 Mev (balloons, rockets and satellites), >500 Mev (ground-based equipment) (see Chapter I). In order to analyze the nature of the spectra of solar particles, it is important to compare the observation data referring to different energy ranges.

Methods of representing the spectra of solar particles were discussed in detail in Section 8. If the spectrum has a power form (with respect to energies or rigidities), the following characteristic features of the spectra of solar protons are important for studying the acceleration mechanisms:

1) constancy of spectra from flare to flare for energies up to a few hundred Mev and increase in the inclination of spectrum at higher energies (A. N. Charakhch'yan [I. 15]);

2) inclination of differential energy spectrum with a break in the region of 20-40 Mev (Biswas et al. [III. 12], Bryant et al. [I. 23]);

3) modification of spectrum with time (Bailey [95]);

4) origin of protons of given energy with increasing angle of arrival (Stazeer [96]);

5) arrival of the most energetic protons earlier than expected provided they are accelerated in the chromosphere or lower corona.

In order to interpret these peculiarities of the spectrum, Waddell [97] suggested a model of acceleration of protons due to shock waves excited in the corona by the heat from the flare. The simultaneous solution of relativistic equations of the motion of protons and the motion of magnetic field, giving rise to shock waves shows that energy of protons can attain a value ranging from a few units to a few hundred Mev. As the energy of protons increases, the probability of their scattering in front of the shock wave also increases. This scattering is naturally disorderly as a result of which the protons coming out to the surface are distributed isotropically. As the energy of shock wave is consumed by scattered protons, the wave weakens and disappears. Waddell also calculated the time of flight of protons through the interplanetary space as a function of heliocentral distance, location of flares, energy liberated and the direction of exit to the surface. The results calculated qualitatively agree with the observed peculiarities of the spectra of solar protons.

As far as the spectra of solar particles with $Z \geqslant 2$ are concerned, Freier and Webber [III. 6] suggested to use a function of the type $\exp(-R/R_0)$ for representing them (see Section 8). On the other hand, by comparing exponential rigidity spectra of protons and nuclei with $Z \geqslant 2$, Biswas and Fichtel [III. 29] showed that, although these spectra have similar form, they are not absolutely identical. The condition $R_{op} = R_{o\alpha}$ in (8. 2) is not always satisfied and the error in this conclusion has been estimated to be $< 0.1\%$. This estimate as well as the results of Section 8 provide a sufficiently solid base to consider it to be less probable that some of the simple spectral forms given by equations (8. 1) and (8. 2) can satisfy the experimental data for solar protons as well as for α-particles and medium nuclei. It should be mentioned that the dependence of distribution of solar cosmic rays on the velocity as well as on the rigidity of particles does not make it possible to consider this conclusion to be final owing to limited modern explanations on acceleration and distribution of solar cosmic rays.

On the basis of experimental data discussed in earlier Chapters, it is possible to make certain quantitative estimates and draw conclusions about the generation spectrum of solar comic rays.

As shown by L. I. Dorman [I. 5] for the February 23, 1956 flare and by Roederer [98] for a number of other flares, two spectral representations (8. 6) and (8. 7) apparently correspond to two types of acceleration processes in the generation region:

1. Statistical processes of imparting momentum to particles trapped in the acceleration region (Fermi mechanism in turbulent fields, acceleration by shock or magnetohydrodynamic waves). These processes, as is well known, distribute accelerated particles according to their energies.

2. Electromagnetic processes of acceleration due to participation of electric fields (for example, betatron effect or acceleration in an electrostatic field); this type of processes act on particles in accordance with their rigidities.

For the first type of processes, the total number of particles in the generation region is determined from the equation:

$$\frac{\partial N(\varepsilon, t)}{\partial t} = \frac{\partial}{\partial \varepsilon}\left(N(\varepsilon, t)\frac{d\varepsilon}{dt}\right) - \frac{N(\varepsilon, t)}{\tau_c} + q(\varepsilon, t), \qquad (19.1)$$

where τ_c -average time of accumulation of particles in the acceleration region;
$q(\varepsilon, t)$- emission function defined by velocity of injection;
$d\varepsilon/dt$ - velocity of accumulation of energy by a particle during acceleration.

Thus, the first term in the right-hand side of equation (19. 1) describes the distribution of accelerated particles, second term, their exit from the acceleration region and the third term, the injection conditions. There exists an upper limit for the velocity of injection:

$$q(\varepsilon, t) = 0 \quad \text{at} \quad \varepsilon > \varepsilon_i, \qquad (19.2)$$

where ε_i is the energy of injection. The rate of acceleration for statistical mechanisms similar to Fermi mechanism is equal to

$$\frac{d\varepsilon}{dt} = \frac{1}{\tau_a}\varepsilon, \qquad (19.3)$$

where τ_a is the characteristic time of acceleration.

If the acceleration stops at time t_0 and if $\tau_c \ll t_0$, a steady state will be attained immediately after the beginning of acceleration: $dN/dt = 0$. The solution of (19. 1) in this case can be written as

$$N(\varepsilon) = K\varepsilon^{-\gamma}, \qquad (19.4)$$

where $\gamma = (1 + \tau_a/\tau_c)$ and

$$K = \tau_a \int_0^{\varepsilon_i} q(\varepsilon)\,\varepsilon^{(\tau_a/\tau_c)}\,d\varepsilon.$$

For the February 23, 1956 flare, it was found that t_0= 5-10 min, $\mathcal{E}_i \sim$ 1Gev, $\mathcal{E}_{max} \sim$ 20 Gev, $\tau_a \sim$ 500 sec, $\tau_c \sim$ 80 sec and index of the spectrum $\gamma \sim 7$ which agree with the experimental data (see Section 2).

For the betatron process of acceleration in which the particles are trapped in the magnetic field increasing exponentially with time:

$$H = H_0 \exp\left(\frac{t}{\tau_0}\right), \tag{19.5}$$

and in this equation the rate of acceleration is equal to

$$\frac{dR}{dt} = \frac{1}{\tau'_a} R, \tag{19.6}$$

similar computations lead to power rigidity spectrum.

Let us now consider the process of acceleration by an electric field in which the rate of acceleration is defined only by the intensity of some average field E_0 not depending on the rigidity of particles:

$$\frac{dR}{dt} = bE_0 = \text{const.} \tag{19.7}$$

In this case

$$\frac{\partial N(R, t)}{\partial t} = -bE_0 \frac{\partial N(R, t)}{\partial R} - \frac{N(R, t)}{\tau_c} + q(R, t). \tag{19.8}$$

For the later stage of acceleration $t \sim t_0$ when steady state is attained, the solution of eqn. (19.8) will be

$$N(R) = \frac{1}{bE_0} \exp\left(-\frac{R}{bE_0\tau_c}\right) \int_0^R q(R') \exp\left(\frac{R'}{bE_0\tau_c}\right) dR'. \tag{19.9}$$

At $R > R_i$ where R_i is the maximum injection rigidity, the integral in the right-hand side of equation (19.9) is a constant and therefore

$$N(R) = K \exp\left(-\frac{R}{R_0}\right), \tag{19.10}$$

where $R_0 = b\, E_0 \tau_c$ and

$$K=\frac{1}{bE_0}\int\limits_0^{R_l} q(R')\exp\left(\frac{R'}{bE_0\tau_c}\right)dR',$$

i. e., an exponential rigidity spectrum similar to the one suggested by Freier and Webber [III. 6] is obtained. According to [III. 6], $R_0 \sim 150$ Mv, $R_{max} = bE_0\tau_c \sim 3$ Gv and therefore, putting $t = 10$ min and $E_0 = 1.6 \times 10^{-4}$ v/cm we get the rate of accumulation of rigidity and the value of τ_c as

$$\left.\begin{aligned} bE_0 &= 5 \cdot 10^6 \text{ v/sec},\\ \tau_c &= \frac{R_0}{bE_0} \approx 30 \text{ sec.} \end{aligned}\right\} \qquad (19.11)$$

Frier and Webber [III. 6] put forward a number of views, which are given below, in favor of formation of the exponential rigidity spectrum on the Sun.

Obviously, propagation of solar particles plays a significant role in the modification of their spectrum. This role will be clear only at that time when a satisfactory model of the interplanetary medium will be formulated. Nevertheless, according to Freier and Webber [III. 6], one fact is very clear: the characteristic rigidity R_0 in the exponential spectrum changes with time during the flare but the spectrum retains its exponential form. Thus, the process of propagation significantly changes the value of R_0 but does not change the exponential form of the spectrum. It facilitates the assumption that the emission spectrum also has an exponential form with characteristic rigidity R_0 which slightly differs from the one measured at the Earth.

Recently Stein and Ney [99] studied continuous spectrum of electromagnetic radiation of the Sun (from radio waves to visible light) during the initial phase of a chromospheric flare. It was shown that this radiation is caused by synchrotron radiation of electrons in solar magnetic fields and its spectrum can be explained only on the basis of the exponential rigidity spectrum for electrons with values of R_0 near to those obtained for protons.

These results require consideration of the possibility that electrons, protons and heavier nuclei have similar exponential rigidity spectra during acceleration in a solar flare. What is the possible mechanism of this acceleration? Fermi mechanism and betatron mechanism are the two most popular methods of acceleration. However, as shown above, these mechanisms lead to power energy or rigidity spectra of accelerated particles. Alfven mechanism which is a very general type of betatron acceleration by considering scattering of particles at small-scale irregularities of the magnetic field also cannot be eliminated. This mechanism must give the spectrum as a power function of the momentum of particles.

Taking into account the difficulties of Fermi mechanism and betatron mechanism in explaining the results [III. 6], it is appropriate to consider briefly other acceleration mechanisms.

The fact, that R (rigidity or momentum per unit charge) is the independent variable in the exponential spectrum, facilitates the assumption that the potential vector A, which in units is equivalent to R, takes part in acceleration process. Electric field E acting for a time t on the particle of charge Ze will impart to this particle a momentum per unit charge determined by the relation

$$\int_0^t E\,dt = \int_0^t \frac{1}{Ze}\left(\frac{dp}{dt}\right)dt = \frac{1}{Ze}\int_0^p dp = \frac{p}{Ze}, \qquad (19.12)$$

under the condition that the particle started accelerating from zero velocity. The electric field can be written as

$$E = -\operatorname{grad}\varphi - \frac{1}{c}\frac{\partial A}{\partial t}. \qquad (19.13)$$

There arises the following question: how can an electric field of sufficient intensity exist and accelerate particles in the region of flares on the Sun? Taking into account the high conductivity of solar plasma, it is difficult to think of a way in which a three-dimensional charge, sufficient for giving rise to a significant electric field, can originate or the induced electric field can accomplish work on particles. Many research workers, for example, Parker [88] studied these questions in great detail.

Most of the observers attribute a flare to an accidental process which, due to its nature, apparently requires fulfillment of special conditions (see Ellison et al [27]). Can such conditions exist which could eliminate the known problems created by the difficulties of existence of electric fields in a highly conductive plasma of a solar flare? A number of research workers give an affirmative answer to this question (see Dangey [70]). Under some special magnetic configurations, the electric field possibly functions within a relatively small volume filled by particles. The total fall of potential in this region and the total number of particles, which could have been accelerated, do not contradict the modern observational data. Conditions for the existence of a discharge are possibly created in a way slightly different from that in the case of the special configuration of field suggested by Dangey. On the other hand, it is necessary to consider the possibility that instantaneous acceleration of solar cosmic rays can take place due to arbitrary fluctuations of electric fields in the flare region especially if it is taken into account that powerful motions of plasma and magnetic fields definitely give rise to the effect of formation of a local three-dimensional charge. In order to explain as to which of these acceleration mechanisms is the main mechanism, it is necessary to have more detailed data on solar plasma and real physical conditions in the flare region.

After indicating the inadequacy of the modern theories of acceleration for explaining the peculiarities of exponential spectrum, Freier and Webber arrived at the following conclusion. The acceleration mechanism, capable of forming above-mentioned rigidity spectra for particles with various charge-to-mass ratios, apparently function at the source if it is considered that electrons, giving rise to synchrotron radiation in the flare, have the same characteristic rigidity R_0 as protons and α-particles during acceleration.

Electric fields of the type (19.11), necessary for exponential spectrum, can possibly be provided by the acceleration mechanism, suggested by S. I. Syrovatskii [90] due to dynamic dissipation of the magnetic field.

As mentioned in Section 8, Freier and Webber [III. 6] put forward the hypothesis according to which rigidity spectra can be related to distribution of particles in the plasma ejected by solar flares. Spectra of high- and medium-energy protons were obtained in [III. 6] by extrapolating the spectrum of plasma particles, i.e., the total spectrum of solar protons includes plasma in the low-energy region. However, as shown by Roederer [98], the mechanism of distribution of solar particles according to rigidity imposes limitations on this hypothesis.

Obviously, in order to draw a final conclusion about the nature of processes giving rise to spectrum of solar particles, it is necessary to know if the spectrum remains exponential up to the processes of modulation in the interplanetary space. The results, obtained from diffusion theory (Section 14. 7), show that the spectrum of solar protons at the source has the form $\sim \mathcal{E}_k^{-\gamma}$ at least in the region of nonrelativistic energies of 10-500 Mev.

20. ACCELERATION MECHANISMS

20. 1 Injection mechanisms: The study of acceleration mechanisms of solar particles, conducted by L. I. Dorman [101, 102], shows that, at reasonable values of acceleration parameters, injection energy is much more than the average thermal energy kT and thus, the fraction of accelerated particles is very low in these cases. By analyzing the condition of injection of particles from the medium in-between magnetic mirrors or magnetic clouds and the condition of injection for acceleration in the magnetic trap, L. I. Dorman [I. 5] showed that solar particles must preliminarily gain energy (protons, up to a few Mev and electrons -- up to $\sim 10^5$ ev) with the help of some non-electromagnetic mechanism. It was concluded that the flux of injected particles will be sufficient for further acceleration to higher energies only if a thermonuclear reaction takes place in the flare (see Section 21).

Recently, liberation of heat of local plasma in the region of flares has been taken as the basic injection mechanism in a number of works. In the case of such an injection mechanism, initial composition of accelerated particles must be the same as the composition of solar atmosphere. From the assumption that the injected particles belong to the upper "tail" of thermal spectrum, it is most probable that the particles participate in the process of basic acceleration in highly ionized state [103, 117].

20.2 Basic acceleration. As mentioned in Section 19, acceleration mechanisms, in which accelerated particles are considered as external with respect to plasma and in which, due to this, participation of injection energy is inevitable, include two processes: magnetomechanical and electromagnetic.

A systematic study of such acceleration mechanisms was conducted by Hayakawa et al. [III.54]. Two ways of energy transfer--regular and statistical-- are differentiated in the acceleration process. The regular method is usually associated with rapid processes; the statistical method is important for understanding the energy spectrum of accelerated particles. The dynamic consideration of acceleration mechanisms is formulated as the study of motion of a charged particle in a given external electromagnetic field.

It was shown that Fermi mechanism of acceleration (change in energy is proportional to the energy of the particle) comes into play in every collision in which the particle is subjected to kinematic action. It is significant to note that there is no correlation with the previous motion of the particle and that only pure (independent) change in energy is observed during every new collision. Since the Fermi process is associated with the change in the longitudinal component of momentum and betatron process, with change in the transverse component, these two cases can exist simultaneously under actual conditions.

The general picture of acceleration of charged particles is considered in [III.54] on the basis of the behavior of a particle in electromagnetic fields of special configurations. All the studied models of magnetic field have the form of magnetic "bottles" with the addition of three-dimensional and time irregularities. In these configurations, the motion of a charged particle without any limitations is represented by three types: rotation about the magnetic line of force, longitudinal displacement along it and azimuthal drift along the surface of the magnetic "bottle".

These types of motion of a particle are unambiguously differentiated when the frequency of the imposed magnetic field is small as compared to the frequency of Larmorov precession, i.e., when the approximation of guiding center is applicable. In this case, change in the energy of a particle in the reference system of the observer will be described by the relation

$$\frac{d\varepsilon}{dt}=(\dot{\varepsilon})_b+(\dot{\varepsilon})_\Phi+(\dot{\varepsilon})_I-(\dot{\varepsilon})_T, \tag{20.1}$$

where

$$(\dot{\varepsilon})_b=\frac{c^2p^2\sin^2\alpha}{2\varepsilon H}\frac{\partial H}{\partial t},$$

$$(\dot{\varepsilon})_\Phi=\frac{c^2p^2\sin^2\alpha}{2\varepsilon H}vH',$$

$$(\dot{\varepsilon})_I=ZecHJ_1,$$

$$(\dot{\varepsilon})_T=-\frac{c^2p}{\varepsilon}\cos\alpha(H/H')\sqrt{J_1(J_1+J_3)}\cos\omega_1.$$

Here $H'=\frac{\partial}{\partial s}H(s,t)$ represents three-dimensional derivative, p is the momentum, v is the velocity of the particle, α is the pitch angle and J and ω_1 are the integral of action and phase of rotation respectively, $(\mathcal{E})_b$ and $(\mathcal{E})_\Phi$ correspond to betatron and Fermi processes respectively; $(\mathcal{E})_I$ represents the effect of induced acceleration and $(\mathcal{E})_T$ describes the acceleration associated with rotation. Average value for ω_1 is used as a rough approximation of the theory when the rotation is considered to be fast. In this case, the last two terms in (20.1) play a negligible role and therefore

$$\left\langle\frac{d\varepsilon}{dt}\right\rangle=(\dot{\varepsilon})_b+(\dot{\varepsilon})_\Phi=a\varepsilon+bvp, \tag{20.2}$$

where

$$a=2\left(\frac{v}{c}\right)^2/\Delta t,\quad b=\left\langle\frac{\sin^2\alpha\left(\frac{\partial H}{\partial t}\right)}{2H}\right\rangle.$$

However, since the path of a particle in the acceleration region significantly depends on the rigidity of particle R, the rate of acceleration should be expressed as a function of rigidity and not of energy:

$$\frac{dR}{dt}=a\sqrt{R^2+\left(\frac{A}{Ze}\right)^2M^2c^4}+bR. \tag{20.3}$$

Here, as mentioned earlier, the first term on the right-hand side explains Fermi acceleration and the second term, betatron acceleration.

The conditions of acceleration of solar particles can be formulated in the form

$$mc^2 < \left(\frac{b}{a}\right)^2 2kT < Mc^2, \qquad (20.4)$$

where M is the mass of the nucleus and m is the mass of an electron. It follows from this that Fermi acceleration is effective for nuclei while acceleration of electrons is caused by the betatron mechanism.

One of the authors of [III.54] (Nishimura), with the help of this model, explained the composition of solar cosmic rays and the observed exponential rigidity spectra: Fermi acceleration predominates at the earlier stage of acceleration while betatron mechanism plays the leading role at the later stage. This model gives a satisfactory explanation to the observed phenomena of acceleration of solar particles. But it is very difficult to explain acceleration of electrons. The reason is that nonrelativistic solution of equation (20.3) in the form (R_i is the initial rigidity)

$$R = \frac{a}{b}\frac{A}{Ze}Mc^2(e^{bt}-1) - R_i e^{bt} \qquad (20.5)$$

after putting in it the values satisfying (20.4), we get $\varepsilon_k = 40$ kev for electrons while energy of electrons is found to be more than a few Mev from the observations on radio emission of solar flares. In order to overcome this difficulty, Nishimura put forward a suggestion that the initial rigidity of particles must correspond not to 10^3 ev as was assumed earlier but to 10^6 ev which corresponds to the electron gas of higher velocities. Rapid betatron process at the beginning of the flare is taken as the injection mechanism. In this case, effectiveness of acceleration will be $b \sim v/\Lambda_e \sim 10^{-1}$ sec^{-1} (Λ_e is the mean free path of electron). The injection process takes place either in the chromosphere or in the lower corona and therefore, the injected electrons can get into the upper corona and lead to radio outbursts of type IV. Consequently, subsequent acceleration of solar particles can take place in the upper corona.

As compared to [III. 54], Sakurai [105] obtained a more complete equation for acceleration of charged particles in the approximation of guiding center, adopted in [III. 54]. The equation is derived from the motion of charged particles in a magnetic field, changing with time and in space. In this case, the change in energy for a particle of energy W is represented by the form

$$\frac{\partial W}{\partial t}=\left(\frac{v_{\parallel}}{c}\right)u_{\perp}\frac{\partial l_{\perp}}{\partial S}W+\frac{p^2c^2}{W}\frac{\sin^2\alpha}{2B}u_{\perp}\nabla B_{\perp}\frac{p^2c^2\sin^2\alpha}{W2B}\frac{\partial B}{\partial t} \qquad (20.6)$$

Here B is the intensity of magnetic field B; $v_{\parallel}$ is the component of the velocity of particle parallel to the magnetic field, $\mathbf{u}$ is the velocity of magnetic field, I is the unit vector parallel to $\mathbf{B}$ and p α and S represent the momentum, pitch angle and length of the arc along the magnetic line of force respectively. The second and third terms in the right-hand side of equation (20.6) describe. Fermi acceleration of first order and betatron acceleration respectively. The first term in the right-hand side of equation (20.6) disappears when the velocity of magnetic field does not have a component perpendicular to the lines of force, i.e., when

$$u_{\perp}\frac{\partial l}{\partial S}=0, \quad u_{\perp}=0. \qquad (20.7)$$

Thus, the first term of (20.6) describes Fermi acceleration of the second order. If the magnetic lines of force are compressed simultaneously in the longitudinal and transversal directions, both the mechanisms--Fermi acceleration of the first and second orders--can function simultaneously.

The equation for the average change of energy of accelerated particles can be transformed into the equation for change of rigidity in the following way:

$$\frac{\partial R}{\partial t}=\frac{(c/v)(a+b)}{ZeW}+bR, \qquad (20.8)$$

where a and b are effectiveness of Fermi acceleration of the first and second orders respectively. It follows from (20.8) that in the relativistic region, Fermi acceleration depends on A/Z while betatron acceleration is defined by rigidity R. It agrees with the results obtained by Hayakawa et al. [III. 54].

Induction mechanisms of acceleration of solar particles as a result of change in magnetic fields were studied by Korff [106]. He showed that, in the case of a field H∼1 gauss, protons and other charged particles can accelerate to energies of the order of many Mev during a period of a few seconds. If this period of acceleration has to be sufficient, the acceleration must take place at altitudes of 10^4 km above the photosphere of the Sun. It does not contradict the conclusion made earlier in the work of P.E. Kolpakov [107] that regions of chromospheric-cum-coronal plasma, situated in boundary regions of the magnetic field of the group of sunspots, are more favorable regions for acceleration of charged particles by induced electric eddy fields.

From the point of view of the possibility of explaining the charge and energy spectra of solar cosmic rays as well as for a more complete description of physical processes observed during solar flares, mechanisms of acceleration of solar particles by shock waves in solar plasma are of great interest. These waves are caused by turbulences in flares and by subsequent emission of fast modifications of hydromagnetic waves, which, as shown by Kiepenheuer [108], become sharper when they get into the corona.

One such mechanisms of the first order was suggested by Schatzman [109]. According to his model, solar particles are accelerated by perpendicular hydromagnetic waves where magnetic field intensifies transverse to the shock front. Let us consider the case when charged particles have superthermal velocities and consequently, when losses at collisions can be neglected to first approximation. In the coordinate system moving with the matter, such a particle rotates in the magnetic field. Intercepting the shock front, the particle, which rotated before the front, is subjected to acceleration, rotates in the medium behind the front, intersects the shock front, again gets accelerated and so on. This effect is possible only if the magnetic field before and at the back of the front is irregular. In this case, as shown by Parker [110], grouping of magnetic fields leads to a stochastic process necessary for movement of some particles along with the shock front. As a result, only a part of them remains behind the front with an energy increased by as many times as the difference between the magnetic fields before and behind the front.

The energy acquired by a particle after covering a distance L along with the shock wave is determined from the relation

$$\varepsilon=\left[\varepsilon_0^2+\left(\frac{300}{4\pi}\bar{\eta}BL\right)^2\right]^{1/2}, \qquad (20.9)$$

where ε_0 is the potential energy of a particle, B is the magnetic field and $\bar{\eta}$ is the amplitude of the shock wave:

$$\bar{\eta}=\frac{\rho_1-\rho_0}{\rho_0}, \qquad (20.10)$$

where ρ_1 and ρ_0 are the densities of the medium before and behind the front respectively. At L = 10^9 cm, B = 50 gauss and $\bar{\eta} = 10^{-1}$, we get $\varepsilon = 1.19 \times 10^{11}$ ev for a proton. The shape of the energy spectrum of accelerated particles is given in the form

$$D(\varepsilon)\sim\exp(-\varepsilon/kT_f), \qquad (20.11)$$

where T_j is the hypothetical temperature determined by the parameters of the shock wave. By comparing the obtained conclusions with the measured data, Schatzman concludes that the hypothetical temperature varies from event to event. Nuclear composition of accelerated particles (only protons and α- particles are considered) also finds a satisfactory explanation on assuming that the relative probability of acceleration of α-particles, as compared to the probability of acceleration of protons, is a direct function of the amplitude of shock wave (20.10).

The theory of acceleration of solar particles by hydromagnetic shock waves was worked out by Wentzel [III] in a well-formulated way. Fermi mechanism of the first order was suggested in which chains of shock waves move across each other with equal amplitudes and with sufficiently smooth structure and then, the magnetic moment of an accelerated particle remains constant evrywhere excepting in those regions of shock points which are considered to be thin as compared to the Larmorov radius of particles. Colliding with such a front, the particles undergo arbitrary accelerating reflections but never get retarded. Obviously, the observed form of two parallel threads will be the most-favorable geometry of flare for such an acceleration model.

Assumption about the constancy of magnetic moment of particles outside the shock fronts requires minimum values of the radius of rotation and rigidity; therefore, the number of particles, injected in the acceleration region with the radius of rotation sufficient for acceleration, depends on the Z/M ratio. In this way, the injection conditions explain the variations of p/α ratio for different events at a constant (within the limits of uncertainty) ratio of other components of solar cosmic rays.

During such a mechanism, the momentum of a particle increases and the increase follows the exponential law as is obvious from the relation

$$\frac{dp}{dt} = 2t_{sh}\nu p. \tag{20.12}$$

Here t_{sh} is the time of existence of the particle being accelerted before the shock front and ν is the total number of reflections accelerating the particle. It is easy to see that equation (20.12) is applicable to nonrelativistic as well as to relativistic energies.

The acceleration spectrum was obtained in [111] by solving the continuity equation for particles leaving the acceleration region and under the condition that the solution is not modified by propagation through solar and interplanetary fields. Here, it was shown that this mechanism can give rise to a number of different spectra [depending upon the form of (20.12)] out of which following are the simplest ones:

$$\left.\begin{aligned} &D_\odot(p) \sim e^{-p/p_0},\\ &D_\odot(p) = p^{-1-\frac{1}{\tau}},\\ &D_\odot(\varepsilon) \sim e^{-\varepsilon/\xi},\\ &D_\odot(\varepsilon) \sim \varepsilon^{-1-\frac{1}{\alpha}}, \end{aligned}\right\} \tag{20.13}$$

where p_0, τ, ξ and α are constants. Spectra for a number of flares of solar cosmic rays have been explained in [111] with the help of equation (20.13). Difficulty of the suggested model, first of all, lies in the estimation of the duration of emission of solar particles from the acceleration region which defines the nature of spectra (20.13). It should however be mentioned that similar difficulties also arise in many other acceleration mechanisms mentioned earlier.

In our opinion, the study of acceleration of cosmic rays by high-frequency turbulency of unsteady plasma (for example, by plasma waves as well as by transverse waves into which the plasma waves get transformed) is very perspective. This question has been considered in a number of works of V.N. Tsytovich [112-114].

The high-frequency turbulency corresponds to the minimum possible scale of turbulency in plasma. Therefore, the particle experiences maximum number of collisions with waves during acceleration as a result of which the acceleration by such a mechanism can be much more effective than acceleration by hydrodynamic turbulency.

As far as mechanisms of generation of high-frequency turbulency of plasma are concerned, there exists a number of possibilities one of which is the generation of high-frequency turbulency by accelerated particles themselves. In the presence of intense vibrations in plasma, i.e., in the nonlinear approximation, there is a possibility of swinging of longitudinal vibrations by cosmic rays. Another possibility of nonlinear generation of plasma waves is realized in the presence of transverse waves in plasma : it is caused by the effect of induced scattering of transverse waves at the accelerated particles by transforming into longitudinal waves. The process of acceleration of charged particles by high-frequency turbulency, in the general case, can be described by diffusion equation [113]

$$\left.\begin{aligned} \frac{\partial f_p}{\partial t} &= \frac{\partial}{\partial p_i} D_{ij} \frac{\partial f_p}{\partial p_j}, \\ D_{ij} &= \int \omega_p(k) N_k^l k_i k_j \, dk. \end{aligned}\right\} \qquad (20.14)$$

Here f_p is the distribution function of particles being accelerated, N_k^l is the number of waves and $\omega_p(k)$ is the probability of wave radiation by a particle. The change in the average energy of a particle being accelerated for isotropic turbulency is obtained as

$$\frac{d}{dt}\langle\varepsilon\rangle = e^2\omega_0^2 \left\langle \frac{c^2}{v^3\varepsilon} \left[\left(1 - \frac{v^2}{c^2}\right) W^l(v) + \frac{2v^2}{c^2} \int_{v_\Phi}^{v} \frac{W^l(v_\Phi)\, dv_\Phi}{v_\Phi} \right] \right\rangle, \quad (20.15)$$

where v is the velocity of the particle, ω_0 is the plasma frequency, $W^l = \int W^l_k dk$ is the density of energy of turbulency and $v_\phi = \omega_0/|k|$ is the phase velocity of plasma waves. From (20.15) follows the general conclusion that, at a given density of energy of turbulency of plasma waves, the higher the phase velocity of plasma waves, the more effective will be the acceleration. For the partial case $v > v_\phi$, change in the energy of the particle being accelerated was obtained in [112] as

$$\frac{d\varepsilon}{dt} = c\frac{\pi}{2} r_0 \lambda_0 \left(\frac{mc^2}{\varepsilon}\right) \varepsilon_{pl} \left[\frac{c^3}{v^3} + \frac{c}{v}\left(\ln\frac{v^2}{v_\Phi^2} - 1\right)\right] \frac{v_\Phi^2}{c^2}, \quad (20.16)$$

where

$$\varepsilon = \frac{mc^2}{\sqrt{1 - v^2/c^2}}, \quad \lambda_0 = \frac{2\pi v_\Phi}{\omega_0}, \quad r_0 = \sqrt{\frac{e^2}{mc^2}}.$$

ε_{pl} is the energy of plasma waves in 1 cm^{-3}

The expression (20.16) almost does not depend on v_ϕ. Therefore, the mechanism of acceleration by plasma waves is practically uninjected, i.e., correctly speaking, injection is defined by a self-regulating process: waves, having high v_ϕ, get accelerated more intensly and damp quickly. There remain the waves with $v_\phi << v_T$ (v_T is the average thermal velocity of electrons). These waves will accelerate particles with $v > v_\phi$ and therefore, plasma waves change whole of the "tail" of initial distribution of particles being accelerated.

If the density of the energy of plasma waves is evaluated according to [112] as

$$\varepsilon_l \sim 10^4 - 10^5 \text{ ev/cm}^3, \quad v_T \sim 3.10^7 \text{ cm/sec}$$

$$v_\phi \sim 3.10^8 \text{ cm/sec}, \quad \lambda_0 \sim 3.10^4 - 10^5 \text{ cm},$$

then

$$\frac{d\varepsilon}{dt} \simeq (10^{-8} \div 10^{-7}) \frac{mc^2}{\varepsilon} \text{ [erg/sec]} \quad (20.17)$$

For Fermi acceleration, a similar estimate gives

$$\frac{d\varepsilon}{dt} \simeq 10^{-18} \frac{\varepsilon}{mc^2} \text{ [erg/sec]} \quad (20.18)$$

It follows from the comparison of (20.17) and (20.18) that the acceleration by plasma waves is more effective than Fermi acceleration of the first order right up to $\mathcal{E} = (0.5\text{-}1.5)\times 10^{11}$ ev (for electrons).

The mechanism of acceleration of particles due to dynamic dissipation of magnetic field, suggested by S.I. Syrovatskii [90], is at the same time an extremely suitable mechanism of plasma turbulization; obviously, specific applications of this mechanism require the analysis of the role of turbulent processes in generation of particles.

Let us mention some quantitative estimates. The particles, external with respect to plasma, will experience accleration due to electric field and retardation due to collisions with plasma particles. For fast particles, there is a possibility of such a situation when acceleration predominates over retardation i.e., the particles "run-away". Critical value of the electric field is determined from the condition at which Ohm's law is applicable to plasma since, when $E > E_{cr}$, the "running-away" particles start losing energy for generation of high-frequency turbulency in plasma and it changes Ohm's law: conductivity is determined not from collisions with plasma particles but from collisions with plasma waves.

Therefore,

$$j_{\text{кр}} = \sigma E_{\text{cr}_1} \tag{20.19}$$

and since

$$j = \frac{c}{4\pi}\,\mathrm{rot}\,\mathbf{H} = \frac{c}{4\pi}\frac{H}{l}, \tag{20.20}$$

where H/ℓ is the gradient of magnetic field observed during a flare, then at

$$\frac{H}{l} > \frac{4\pi}{c}\, j_{\text{cr}_1} = 4\pi e n\left(\frac{kT}{mc^2}\right)^{1/2} \tag{20.21}$$

particles may get accelerated by high-frequency turbulency in which case heavy multicharge ions are accelerated more effectively than light ions.

It is highly probable that the condition (20.21) explains unusual increase in the intensity of heavy nuclei recorded in the experiments of L. V. Kurnosova et al. (see Section 9).

The condition of dynamic dissipation accompanying "run-away" of particles was found by S. I. Syrovatskii [90] in the form

$$\frac{H_0}{n_0} k^2 \beta^{(3k-2)k} r_s^{-2k} \geqslant \pi^2 \alpha \left(\frac{\sigma}{n_0 c} E_{\mathrm{cr}} \right). \tag{20.22}$$

Here r_s is the distance at which Alfven velocity becomes equal to the velocity of sound for the case of k currents of same density giving rise to neutral line; α and β are constants in the expression for the potential of displacement currents in the region of neutral line.

From this point of view, a more rigid condition of dissipation, at which all plasma particles start accelerating, is realized at higher potentials of the field when the magnetic field does not freeze into plasma:

$$\frac{H}{l} > \frac{4\pi}{c} j_{\mathrm{cr}} \underset{2}{=} \frac{4\pi}{c} nec. \tag{20.23}$$

This condition apparently means acceleration of particles to relativistic velocities.

Plasma unstabilities in chromospheric flares were studied by Ya. I. Kolesnichenko and A. K. Yukhimuk [115]. By studying the stability of longitudinal vibrations of plasma during flares in the case of thermonuclear reactions taking place in them, the authors [115] showed that the plasma in a flare becomes unstable when the density of the products of thermonuclear reactions crosses the critical value. Duration of development of unstability is significantly less than the characteristic relaxation time. This unstability leads to generation of cosmic rays at the concluding stage of a flare.

M. A. Gintsburg [116] put forward a mechanism of acceleration of electrons and ions in nonlinear magnetohydrodynamic currents, i. e., isolated pulses of magnetic field and plasma (the so-called solitones recently obtained even under laboratory conditions). Electrical eddy field, arising due to rapid changes in magnetic field (rot $E = -\frac{1}{c}\,\partial H/\partial t$) is the physical cause of acceleration.

Important estimates on the number of particles being accelerated in an ionized gas under different acceleration mechanisms were obtained by A.V. Gurevich [117].

Recently, B.A. Tverskoi [182] studied scattering, diffusion and acceleration of nonrelativistic charged particles in turbulent plasma by assuming that turbulence is hydromagnetic and its characteristic dimension is much more than Larmorov radii of particles being accelerated. It was shown that, if fluctuation spectrum is $dh^2/df \sim f^{-\gamma}$, scattering at all values of γ is caused by cyclotron resonance. Acceleration of particles at $\gamma > 2$ is defined by Fermi mechanism while at $\gamma \leq 2$, Fermi mechanism as well as cyclotron resonance play a significant role. In unlimited plasma, acceleration leads to an increase in the internal dimension of turbulence and to a corresponding reduction in the number of resonance particles being accelerated. In the limited plasma, a steady distribution is established and dissipation of the energy of turbulence is caused by diffusion of most energetic particles from the turbulent region. In [182], the effects of turbulent diffusion and acceleration of particles in the interplanetary medium have been studied, equilibrium spectrum of hydromagnetic fluctuations $dh^2/df \sim f^{-2}$ has been obtained on the basis of experimental data, diffusion coefficient and spectra of accelerated particles in the energy range of 10^{-2}-10^2 Mev have been calculated and the relation between the rate of dissipation of turbulent energy and parameters of fluctuation spectrum has been studied. On the basis of results [182], it is apparently possible to explain the effects of increases in the flux of low-energy protons usually observed simultaneously with the commencement of a geomagnetic storm (i.e., at the time of arrival of disturbed plasma to the Earth) (see Section 10.5).

A.K. Yukhimuk and M. Kh. Kats* studied the possibility of acceleration of charged particles during their scattering at electromagnetic fluctuations of interplanetary plasma. It is known that the higher the degree of fluctuations in plasma, the higher will be the rate of change of energy of a particle moving in turbulent plasma. It was shown that the change in the energy of a particle is maximum at $v \cos\varphi_0 \sim u_e$ where v is the velocity of the particle, u_e is the velocity of plasma electrons and φ_0 is the angle between the directions of v and u_e. It was found in this case that if Alfven velocity $v_A << c$ the effect of magnetic field on the change in the energy of a moving particle can be neglected. This work mainly differs from [182] in the fact that the nature of spectral distribution of fluctuations facilitates the study of interaction of charged particles with turbulent plasma in general without introducing detailed properties of the spectrum of turbulence while in [182], a study of similar problems required detailed knowledge of the spectrum of turbulent fluctuations of plasma. The interaction of charged particles with turbulent plasma in the presence of radiation was studied in [112-114]. Significant acceleration of ions is the main hindrance in such an approach. Uncertainty of selection of the parameter $b = k_0^{-1}$ (k_0 is the maximum value of wave vector), providing divergence of the expression for the change in the energy of a particle, is the main drawback of the work of A.K. Yukhimuk and M. Kh. Kats.

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* *Personal communication.*

Recently V. Ya. Davydovskii and E.M. Yakushev [186] studied the mechanism of acceleration of particles by electromagnetic waves of variable propagation velocity. The acceleration takes place due to an increase in the velocity v_M of magnetic trap (wave) in the laboratory system of reference (longitudinal velocity of the particle $v_{\parallel} = v_M$). The accelerating traps can be caused by electromagnetic waves in plasma, concentration of which changes slowly along the direction of propagation. Initial and final energy of the particle being accelerated ε_i and ε_f, are related to corresponding values of concentration n_i and n_f by the relation $\varepsilon_f / \varepsilon_i = (n_i / n_f)^{1/2}$.

On the Sun in the region of chromospheric flares, $n_i = 10^9$ cm^{-3} while in the upper corona $n_f = 10^6$ cm^{-3} as a result of which $\varepsilon_f = 10^{10}$-10^{11} ev which does not contradict observations.

As shown in [186], whole of the wave energy is, in some cases, transferred to trapped particles, i.e., sometimes, the sources of cosmic rays where this mechanism functions, may not emit electromagnetic radiation responsible for acceleration of particles. Moreover, since acceleration depends on the velocity of the particle (and not on energy), mainly heavy nuclei will be accelerated.

21. NUCLEAR PROCESSES IN CHROMOSPHERIC FLARES

Most of the present theories of the processes, taking place in chromospheric flares, assume the existence of a high-temperature zone in the flare where solar plasma, in principle, can get heated to thermonuclear temperatures $\sim 10^7$ °K. The possibility of some thermonuclear reactions in these high-temperature zones was, for the first time, pointed out by A. B. Severnyi and V.P. Shabanskii [78].

Reactions of the synthesis of deuterium ${}_1D^2$ can proceed in two ways:

$$D + D \begin{cases} \nearrow He^3 + n \\ \searrow T + p \end{cases} \tag{21.1}$$

An energy of 3.25 Mev and 4.0 Mev respectively is liberated during these reactions. There takes place a secondary reaction between deuterium and tritium

$$D + T \rightarrow He + n, \tag{21.2}$$

during which an energy of 17.6 Mev is liberated. The reaction (21.2) has resonance nature and its extent is more than that of the reaction (21.2).

The yield of DD-reaction was evaluated by A. B. Severnyi and V. P. Shabanskii [78]:

$$tP = 1.25 \times 10^3 \text{ particle/cm}^3. \tag{21.3}$$

Here $t \approx 10^3$ sec is the time of reaction and P is the number of thermonuclear reactions taking place in 1 cm^3 during 1 sec. The last parameter is determined from the relation

$$P = \frac{n_D^2}{2} \overline{v\sigma}, \tag{21.4}$$

where $\overline{v\sigma}$ is the product of the relative velocity of nuclei with the effective size of the reaction averaged for the Maxwell distribution of velocities and n_D is the concentration of deuterium nuclei in plasma taken equal to $10^{-5} n_H$ (n_H is the concentration of hydrogen nuclei).

If the estimate (21.4) is correct, then during the whole the process, DD-reaction in flare region can, in the case of a strong flare, give rise to 10^{32}-10^{33} particles.

B.M. Vladimirskii and A.B. Severnyi [118] confirm that practically all neutrons, formed due to DD-reaction following the first channel of (12.1), are captured by H (n, γ)D-hydrogen and therefore, they get time to retard to an energy of the order of a few Mev before leaving the flare region. Here, the size of this region is assumed to be equal to $\sim 10^7$ cm.

In this case, deuterium burns up only along the second channel of reaction (21.1) in which deuterium does not get reduced by the protons accelerated in the reaction since all the protons lose their energy before receiving it from neutrons participating in the (p, n) reaction.

The two processes -- capture of protons by hydrogen and formation of deuterons as a result of nuclear fission of nuclei of the oxygen group by protons with $\mathcal{E}_k \sim 10^8$ ev -- are the main processes leading to formation of deuterium nuclei in the solar atmosphere. It has been shown that effectiveness of these processes is not sufficiently high as compared to the rate of burning-up of deuterium in thermonuclear reactions.

Other possible reactions, taking place in light nuclei at a temperature of about 3×10^7 °K (Table 21.1), were studied in [118] on the basis of the following relation for a number of nonresonance thermonuclear reactions in a unit volume per sec:

$$P = 434 \rho X S_0 (\bar{A} Z_1 Z_2)^{-1} \tau^2 e^{-\tau}, \qquad (21.5)$$
$$\tau = 42{,}5 \left[(Z_1 Z_2)^2 \bar{A} \right]^{1/3} T^{-1/3},$$

where ρ - density of the medium taken approximately equal to 10^{14} cm^{-3};

χ - weight concentration of bombarding nuclei;

$A = \frac{A_1 A_2}{A_1 + A_2}$ - reduced mass in atomic units;

S_0 - constant expressed in ev. barn;

T - temperature in the units 10^{6}°K;

Z_1 and Z_2 - charges of the nuclei.

The possible time of burning-up of Li in this type of reactions was found to be ~ 10^{10} years. However, as assumed earlier by I.G. Shklovskii [119], Li nuclei are simultaneously formed furing nuclear fission and this process is more effective.

It was concluded in [118] that the above-mentioned processes must lead to burning-up of D and accuumulation of Li, Be and B in the solar atmosphere as a result of flare activity. However, the existing data on the abundance of light nuclei in solar cosmic rays do not confirm this conclusion.

Let us now consider recent experimental data on the abundance of hydrogen and helium isotopes in solar cosmic rays which can take part in thermonuclear reactions taking place in chromospheric flares.

Tilles et al. [III. 31] mentioned the detection of a significant amount of T in the casing of "Discoverer-17" satellite after the November 12, 1960 flare. It was established that the observed T/p ratio for energies more than 30 Mev/nucleon is of the order of (1 4)x10^{-3}. This value of T is undoubtedly more than that which could be caused by local nuclear interactions. It was later shown that 80% of the tritons observed in "Discoverer-17" casing were secondary and therefore, the actual value of the T/p ratio must be $\leqslant 10^{-3}$. It corresponds to Biswas's results [I. 57] who found that $T/p \leqslant 10^{-3}$ in the range of 20-45 Mev/nucleon.

As a result of balloon measurements on the value of T by nuclear emulsion method during the July 18, 1961 flare, Waddington and Freier [I. 28] evaluated the upper limit of the T/p ratio

TABLE 21.1

Velocity of reactions P taking place in light and heavy nuclei at T ~ 3×10^7 °K

Reaction 1	S_0	A	B	τ	p	n_x/n_H	P, $cm^{-3}\ sec^{-1}$
$Li^6(p, D)He^3$	$5 \cdot 10^6$	$6 \cdot 10^{12}$	84,1	25,72	$6.1 \cdot 10^{-10}$	$1,4 \cdot 10^{-12}$	$8,6 \cdot 10^{-8}$
$Li^7(p, D)He^4$	$1 \cdot 10^5$	$1,2 \cdot 10^{11}$	84,7	25,90	$1.0 \cdot 10^{-11}$	$3,5 \cdot 10^{-13}$	$9,5 \cdot 10^{-9}$
$Be^9(p, D)2\alpha$	$3 \cdot 10^7$	$3 \cdot 10^{15}$	103,6	31,68	$7,7 \cdot 10^{-12}$	$2 \cdot 10^{-10}$	$1,5 \cdot 10^{-7}$
$Be^9(p, D)Li^6$							
$N^{15}(p, \alpha)C^{12}$	$1 \cdot 10^6$	$1,7 \cdot 10^{14}$	153,1	46,82	$1,2 \cdot 10^{-17}$	$9,4 \cdot 10^{-17}$	$4,1 \cdot 10^{-11}$
$O^{17}(p, \alpha)N^{14}$	$2 \cdot 10^5$	$3 \cdot 10^{11}$	167,0	51,07	$3,0 \cdot 10^{-22}$	$9,1 \cdot 10^{-4}$	$1,1 \cdot 10^{-14}$
$O^{18}(p, \alpha)N^{15}$	$1 \cdot 10^8$	$1,5 \cdot 10^{14}$	167,0	51,07	$1,5 \cdot 10^{-19}$	$9,1 \cdot 10^{-4}$	$27 \cdot 10^{-11}$
$F^{19}(p, \alpha)O^{16}$	$1 \cdot 10^9$	$1,5 \cdot 10^{16}$	181,0	55,35	$2,1 \cdot 10^{-20}$	$9,1 \cdot 10^{-8}$	$2 \cdot 10^{-14}$

$A = 434 S_0 B^2 (\bar{A} Z_1 Z_2)^{-1}$; $B = 42.5\ (\bar{A} Z_1^2 Z_2^2)^{1/2}$

n_x - concentration of bombarding nuclei of type x;

p - probability of the reaction for a path L.

as 0.6x10^{-3} for $\varepsilon > 50$ Mev/nucleon and explained the difference between this result and the data of "Discoverer-17" by the effect of the change in the composition of solar particles for different flares. They suggested that such an effect, observed for α/p ratio in many experiments, must also exist for D/p ratio (since, from the point of view of rigidities, deuterons do not differ from α-particles) and for T/p ratio (since magnetic field has a weaker effect on T than on α-particles).

The relative abundance of D, found in [I. 28], was D/p $\leqslant$ 1.4x10^{2} at a constant rigidity and D/p $\leqslant$ 1.4x10^{-3} for energies $>$ 69 Mev/nucleon. The expression for the change in Γ_{Dp} ratio above a particular energy per nucleon is given in [I. 28] in the form

$$\Gamma_{Dp}(\varepsilon)=\Gamma_{Dp}(R)\exp\left[\frac{\pi}{R_0}\left(\frac{A_D}{Z_D}-\frac{A_p}{Z_p}\right)\right], \tag{21.6}$$

where

$$\pi=\{\varepsilon(\varepsilon+2m_0c^2)\}^{1/2}.$$

It is obvious from (21.6) that $\Gamma_{Dp}(\varepsilon)$ increases with time by more than 10 times in the range 0-100 Mev; therefore, it is difficult to compare the values obtained in different experiments.

Much less is known about the abundance of helium isotopes in cosmic rays. During the radiochemical study of the material of the casing of "Discoverer-17" satellite, Schaeffer and Zähringer [I. 56] found relatively large amount of helium nuclei: He^3/He^4 ($>\varepsilon$) $\sim$ 0.2. These observations are difficult to interpret due to the necessity of introducing corrections for the eastern effects. The authors [I. 56] however confirm that the ratio obtained by them corresponds to the actual ratio with an accuracy up to the multiplication factor 3.

Recently Biswas and Fichtel [III. 37] showed that the amount of He^3 in the experiment [I. 56] corresponds to flux which is 10 times the total flux of all helium nuclei i.e., 4x10^7 cm^{-2}. sec^{-1}, in energy range 40-105 Mev/nucleon. Authors [III. 37] cite convincing arguments in favor of the fact that the actual value of the He^3/He^4 ratio is $<10^{-2}$.

Regardless of the above differences in the abundance of He isotopes in solar cosmic rays, it can be confirmed that equilibrium abundance of tritium in solar atmosphere, just like that of helium isotopes, must be much less than the value obtained in above-described experiments.

It can be assumed that these elements are the products of fragmentation of α-particles and heavy nuclei appearing during nuclear interactions at the time of their propagation through the solar atmosphere. If the hypothesis of preferred acceleration of heavy nuclei is not taken into consideration, the low value of H/α ratio (~2%) compels us to disregard the products of fragmentation of heavy nuclei. The amount of matter which α-particles must cover to get the ratio $T/p(>\mathcal{E}) \sim 4 \times 10^{-3}$ is equal to 1.3 g/cm^2 (8×10^{23} $atom/cm^2$) according to the estimates of Biswas and Fichtel [III. 37] and about 10 g/cm^2 according to the data of Fireman [120]. These values are not in agreement with those required for explaining the actual absence of light nuclei in solar cosmic rays (~ 0.1-0.2 g/cm^2). It is clear that in the case of such an approach, the theory of fragmentation cannot explain the observed amounts of tritium and helium isotopes.

Fireman [120] suggested that the observed D, T and He^3 nuclei are the products of quasithermonuclear reactions, taking place in the solar atmosphere near the flare zone. Reaction $H^1(\alpha, D)He^3$ injecting deuterium and reaction $H^1(\alpha, T)H^1$ giving rise to tritium are mentioned as an example. Calculations given in [120] show that in the case of these reactions, it can be expected that D/p (>30 Mev/nucleon) $\sim 10^{-2}$ and T/p (>30 Mev/nucleon) = 4×10^{-3}. From this, we get the ratio D/p (>69 Mev/nucleon) $\sim 5 \times 10^{-3}$ which slightly differs from the corresponding experimental value of 1.4×10^{-3} [I. 28]. This difference can however be explained by taking into account the difference between flares. As confirmed in [120], these reactions can take place in the region of flares where the initial density is sufficient to stop the acceleration of α-particles and heavy nuclei but where protons can get accelerated so as to participate in nuclear interactions. Further the density of these regions reduces with time as a result of which additional acceleration of the products of these reactions becomes possible.

Thus, in spite of certain complications, the study of thermonuclear reactions in the regions of chromospheric flares can be very useful for explaining the composition of solar cosmic rays and for formulating a theory of acceleration of particles on the Sun.

22. ELECTRON COMPONENT OF SOLAR COSMIC RAYS

22.1 Experimental data on solar electrons. The discovery of primary electrons in cosmic rays by Meyer and Vogt [121] and by Earl [122] has given rise to the question of their origin: as to whether they are solar or galactic. The study of variations in the intensity of electrons can play an important role in solving this problem.

Fig. 22.1 shows the results of balloon measurements obtained by Meyer and Vogt [121] on August 22 and September 8 and 15, 1960 for proton beams with R = 370-890 Mv and for primary electron beams with R = 100-1000 Mev. Data of continuous recording of the intensity of neutron component at Deep River (at the sea level) have also been given in the same Fig.

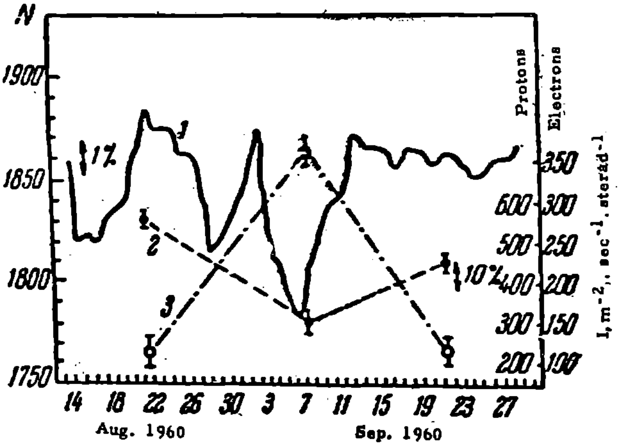

Fig. 22. 1. Cosmic-ray variations in August-September, 1960:

1 - counting rate of neutron monitor at Deep River (left scale); 2 - intensity of primary electrons with R = 100-1000 Mv over Churchill; 3 - intensity of protons with R = 370-890 Mv over Churchill;

The measurements of September 8, 1960 were conducted during the Forbush effect 5 days after the powerful September 3, 1960 solar flare. It may be seen from Fig. 22.1 that while the flux of protons on 8 September increased significantly (due to arrival of particles from the solar flare)*, the flux of electrons decreased by 40%. It means that the primary electrons have the same origin as galactic protons and the modulation mechanism, leading to Forbush reduction, has the same effect on them.

Observations on the variations in electron flux during solar flares can give an unambiguous answer to the question of the origin of electrons. From this point of view, results of Meyer and Vogt [123] are of great significance. They showed that a significant flux of electrons was observed on July 22, 1961 in the stratosphere over Churchill.

Data for the quiet day of August 2, 1961 are also given in [123] where, according to the data of neutron monitors, significant chromospheric flares and outbursts were not observed. Conversion from absorption curve (on the basis of the difference in July 22 and August 2, 1961 curves) to the energy spectrum gives the dependence $dN/d\mathcal{E}_k = 2\text{x}10^4\ \mathcal{E}_k^{-2} m^{-2} sec^{-1}$ $sterad^{-1} Mev^{-1}$ (Fig. 22.2) for the flux of solar electrons.

This increase is most probably related to chromospheric flares of class 3^+ which were observed on July 18 and 20, 1961 and were accompanied by an increase in the intensity of neutron component on the Earth's surface. It should be mentioned that the class 3 flare observed on July 21, 1961 did not lead to any outburst in the stratosphere or on the Earth's surface and therefore, this increase in the flux of electrons is apparently not associated with this flare.

Let us study the results of other measurements taken after 1961.

During the balloon measurements on July 28, 1963 over Churchill, Freier and Waddington [126] also detected some amount of electrons but their intensity is in agreement with the

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* *According to [121], if the effect of flare is eliminated, the flux of galactic protons during this period decreases by 9%.*

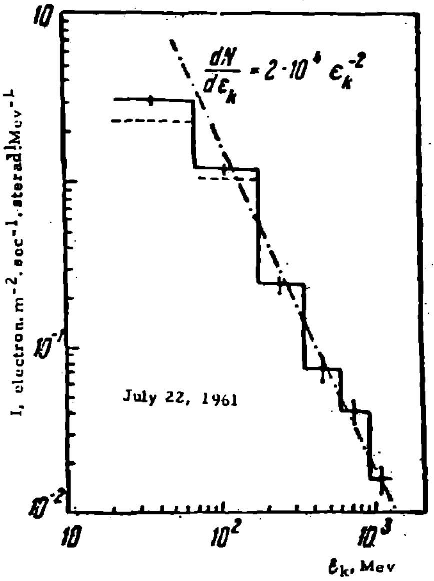

Fig. 22.2. Differential energy spectrum of electrons from a solar flare according to July 22, 1961 observations. Dotted lines are obtained after introducing corrections for the possible role of protons interacting in lead and over it.

results obtained earlier by other authors. The problem of considering secondary electrons in atmosphere was apparently not solved. Without introducing the corrections for formation of secondary electrons, the total intensity of electrons in the energy range $0.13 \leq \varepsilon \leq 5$ Gev at a depth of 2 g. cm^{-2} in the atmosphere was found to be equal to 63±26 m^{-2}. sec^{-1}. $sterad^{-1}$.

During 1964-1966, Anderson and Lin [127], with the help of "IMP-1" and "IMP-3" satellites, recorded 10 events of the appearance of electron beams with $\varepsilon_k > 40$ kev in the interplanetary space (Table 22.1). Seven of these events are characterized by rapid increase in the flux during 15 to 30 mintues and by subsequent slow decrease during several hours. The maximum intensity of electrons in some cases varied between 1-1000 cm^{-2}. sec^{-1}. $sterad^{-1}$.

Out of the ten events recorded, six were associated with small chromospheric flares of class 1^-, 1 and 1^+. One of these events was accompanied by intense absorption of radio noises while the corresponding solar flare was situated near the central

TABLE 22.1

Flux of solar electrons with $\mathcal{E}_k \geqslant 40$ kev in the interplanetary space and in the tail of the Earth's magnetosphere

Date of measurements	Time of increase in the flux of electrons, UT	Heliocoordinates of the flare	Class of solar flare	Maximum intensity of electrons, $cm^{-2} \cdot sec^{-1} \cdot sterad^{-1}$	Delay in the arrival of electrons to the Earth's orbit, min.
		Increases in the interplanetary space			
March 16, 1964	16.40	5°N, 75°W	1	750	38
May 25, 1965*	23.20	19°N, 69°W	1	80	33
June 5, 1965*	19.10	-	1-	180	39
June 13, 1965*	02.58	-	-	10	-
October 8, 1965	16.28	21°N, 84°W	1	230	31
December 25, 1965	06.47	9°N, 29°W	1	250	32
December 29, 1965	12.45 ± 20	10°N, 60°W	1+	25	30
December 30, 1965	01.06	9°N, 68°W	1-	300	44
January 17-28, 1966	Many events	-	-	1000	-
March 19-25, 1966	-do-	-	-	3000	-
		Increase in the tail of the magnetosphere**			
March 14, 1966	14.50		1B	80	33
March 19, 1966	22.27		2B	35	35
March 24, 1966	02.40		3B	5700	19
March 24, 1966	19.29		3B	640	23
March 26, 1966	19.19		2B	350	38

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[*] These data were obtained by Van Allen and Krimigis [128] on "Mariner-4" at a distance of 1.5 a.u. from the Sun

[**] Heliocoordinates of flares are not given in [183].

meridian. The remaining five events were associated with flares situated far-off towards west of the central meridian. Average location of flares corresponded to 62°W which is very close to the expected location if the electrons propagate along the spiral lines of the interplanetary field.

A strong initial anisotropy was observed in all the cases while in some of them, the anisotropy lasted for at least 15 hours. These observations show that the electrons, moving from the Sun to the Earth, are related to the lines of forces of the interplanetary magnetic field. Flux of electrons usually increased during 0.5-1 hour and slowly decreased during 1-2 days. The events observed 6 hours after the commencement of the outburst cannot be described by Krimigis diffusion model [IV. 28].

The time of propagation of electrons from the Sun to the Earth is small -- in all about 20-40 minutes. This fact is against effective scattering and diffusion of electrons in the interplanetary space. Some events, associated with flares on the east of the central meridian, were also observed. Simultaneously, powerful radio zones, which are possibly caused by diffusion and accumulation of electrons in the solar atmosphere, were observed in the western hemisphere of the Sun at a frequency of 169 MHz.

Table 22.1 also shows five events of increases in the flux of electrons which were observed by Lin and Anderson [183] on "IMP-3" in the tail of magnetosphere at distances of 5-20 r_E. The time of propagation of electrons in these cases also was 20-40 minutes. The observed anisotropy of these beams is in agreement with the motion of electrons from the tail inside the magnetosphere to the Earth, i.e., lines of force of the geomagnetic tail are apparentely associated with the lines of force of the interplanetary field. At the maximum energy of electrons equal to 150 kev, the maximum length of the tail of magnetosphere will be equal to 0.25 a.u.

On the basis of these observations, Anderson and Lin arrive at the following conclusions:

1. Many small flares emit a large amount of electrons in the interplanetary space.

2. The region of propagation of electrons in the interplanetary space is limited by a curved conical surface of half aperature angle from 15 to 20° and the axis of this cone is curved in the same way as the lines of force of the interplanetary field.

3. The beam within this cone is anisotropic from where it follows that the simple isotropic model of diffusion cannot be used for explaining migration of electrons in the interplanetary space.

4. In order to explain the presence of electrons, caused by flares near the central meridian, on the Earth, it is necessary to assume that the electrons migrate in the solar atmosphere.

Three events of impulse emission of solar electrons with $\mathcal{E}_k \sim 40$ kev which were recorded with certainty are analyzed in detail in the work of Van Allen and Krimigis [128]. The observations were taken with the help of the equipment installed on the spaceship "Mariner-4" which moved towards the Mars. The energy threshold of the equipment was about 40 kev for electrons. At the time of measurements, "Mariner-4" was situated in the interplanetary space at a large distance from every planet of the solar system.

Increases in the flux of electrons were observed on May 25-28, June 5-7 and June 13-14, 1965. Fig. 22.3 shows the time variation of the counting rate of electrons on June 13-14, 1965 for detectors of energy thresholds $\gtrsim 45$ kev (1) and $\gtrsim 40$ kev (2) as compared to readings of detector 3 which practically did not record electrons and was sensitive only to protons with $\mathcal{E}_k = 0.5$-11 Mev. These results were obtained without considering the background. The intensity of electrons before the commencement of outburst is shown by dotted lines.

It may be seen from Fig. 22.3 that the recorded outbursts were caused by electrons having $\mathcal{E}_k \gtrsim 40$ kev and a sharply falling spectrum. The maximum values of the intensity of electrons on May 25, 28, June 5-7 and June 13-14, 1965 were equal to 80, 58 and 5 cm^{-2}, sec^{-1}, $sterad^{-1}$ respectively while the angular distribution was more or less isotropic.

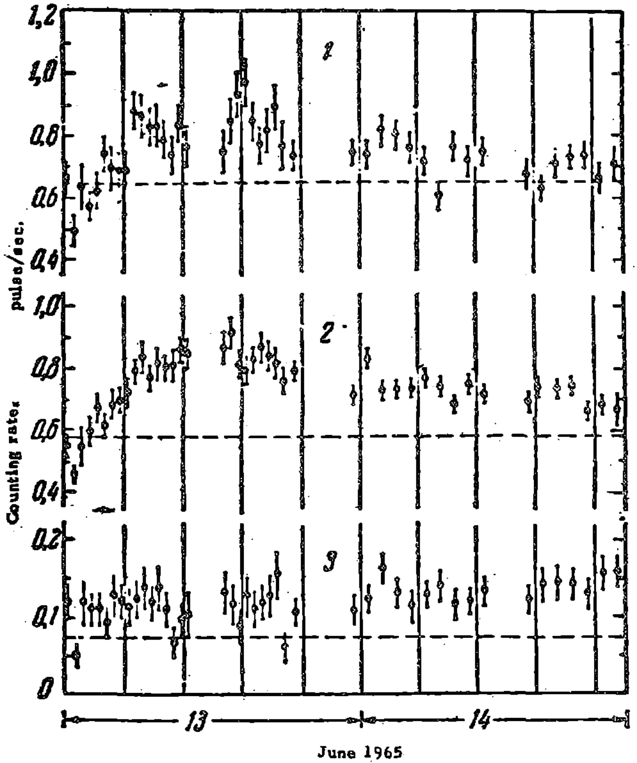

Fig. 22. 3. Increase in the flux of solar electrons with $\mathcal{E}_k \geqslant 40$ kev on June 13-14, 1965. Counting rate before the flare is shown by dotted lines.

Based on the analysis of data on solar activity and geophysical effects during measurements, the authors [128] arrive at the conclusion that the increases in the intensity of electrons were apparently caused by their impulse emission from the Sun's atmosphere almost at the same time when outbursts of radio emission and X-rays were observed.

On the basis of diffusion model of propagation of electrons with $\mathcal{E}_k \geqslant 40$ kev, it is possible to estimate their total number at the time of emission. These estimates give about 10^{34} electrons for May 25 and June 5 events and 10^{33} electrons for the June 13 event. The problem of propagation of electrons is considered in detail in Section 22.2.

Thus, measurements of Van Allen and Krimigis [128] confirmed the earlier assumption about the emission of electrons of nonthermal energies by the Sun. These electrons can serve as a new means for studying the structure of the interplanetary magnetic field and physics of solar flares.

Simultaneously with the increase in the flux of solar protons, small increases in the flux of electrons of energy of the order of tens of kev at the threshold sensitivity of equipment were also recorded by Arnoldy et al. [IV.9] on "Pioneer-5" during the end of March and the beginning of April 1960.

It is reported in the work of Arnoldy et al. [129] that simultaneously with the increase in radio noises on June 5, 1965, the ionization chamber "OGA-A" recorded an outburst of X-ray radiation. Within an hour after the flare, counting rate of the ionization chamber increased by 13%. At this time, the satellite was situated beyond the magnetosphere at a distance of 140,000 km from the Earth. A comparison with the results of observations on electrons from the same flare by Geiger counters on "Mariner-4" showed that the increase in counting rate is apparently caused by electrons having $\mathcal{E}_k > 600$ kev. The maximum flux of these electrons recorded on "OGO-A" is of the order of 1.3 cm^{-2} sec^{-1}. The flux of electrons with $\mathcal{E}_k > 600$ kev at a distance of 1.5 a.u. from the Sun was found equal to 0.42 cm^{-2} sec^{-1}. On comparing these data with the observation results of "Mariner-4" for electrons with $\mathcal{E}_k \gtrsim 40$ kev, the author [120] obtained the extrapolated spectrum of electrons at a distance of 1.5 a.u. in the form $I(>\mathcal{E}_k) \sim \mathcal{E}_k^{-2.7}$.

Other measurements on electrons, not related to solar wind, were made in the range of energies more than a few Mev (for example, in the above-mentioned work of Meyer and Vogt [124], solar electrons were measured with the help of balloons in the range $\mathcal{E}_k = 100$-1000 Mev during July 22 and August 1, 1961 flares).

Interplanetary electrons with $\mathcal{E}_k = 3$-12 Mev were studied in detail by Cline et al. [130] with the help of "IMP-1" ("Explorer-18") satellite during the period December 1963-May 1964. The distance of the satellite from the illuminated side of the Earth in the apogee was equal to 193,000 km and therefore, the geomagnetosphere had no effect at all. Fig. 22.4,a shows the energy spectrum of electrons, obtained at a distance of 125,000 km from the Earth for the period November 27-30, 1963 when their flux was minimum and no variations were observed. The flux spectrum of electrons, obtained after subtracting measurement data of January 9-12, 1964 from the corresponding data for January 13-16, 1964 is shown in Fig. 22. 4, b for comparison. The January 13-16, 1964 outburst, detected in this way, was not accompanied by an increase in the flux of γ-rays or cosmic rays.

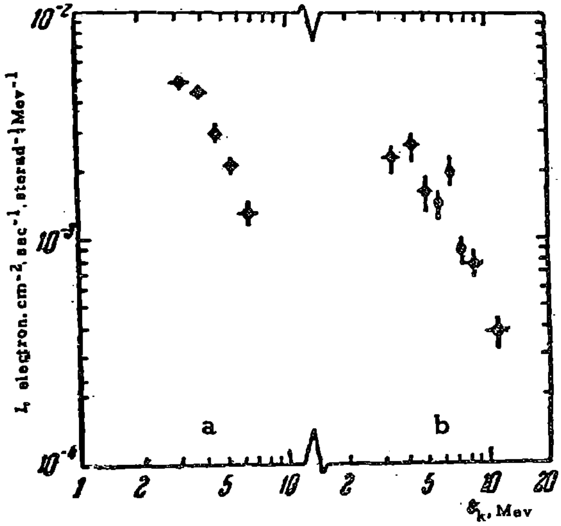

Fig. 22. 4. Energy spectrum of electrons at a distance of 125,000 km from the Earth:

a - November 27-30, 1963; b - January 9-12, 1964.

Similarity of spectra for two cases, shown in Fig. 22. 4, makes it possible to consider that the electrons of quiet beam and the observed outburst have the same origin. The integral intensity of electrons with $\mathcal{E}_k = 2.7-7.5$ Mev was found equal to 210±10 electron. m^{-2} sec^{-1}, sterad^{-1} while the intensity of additional beam at $\mathcal{E}_k = 3-12$ Mev was equal to 100 ± 10 electron m^{-2}, sec^{-1}, sterad^{-1}, i.e., the relative increase was about 50%.

Although the observed cases of outbursts were mainly caused by cosmic electrons, Cline et al. [130] do not eliminate the possibility of their solar origin. In this connection the following observations must be kept in view.

Firstly, relativistic electrons must be generated at most of the part of the surface of solar atmosphere. In this case, more powerful beams of solar plasma (containing recurrent beams of solar protons) will hold lesser number of electrons than the weaker beams. Moreover, retardation of electrons can be more effective in the powerful plasma beam than in the weak beam. On the other hand, electrons may be associated with the development of new regions of sunspots. However, Cline et al. [130] could not correlate the observed increases in the flux of electrons with solar activity.

Increases in the flux of solar electrons with $\mathcal{E}_k > 30$ kev and $\mathcal{E}_k > 60$ kev were recorded by N.L. Grigorov et al. [185] by "Luna-11" satellite on September 1 and 8, 1966. Basic data on these effects are given in Table 22.2. Protons with $\mathcal{E}_k > 1.0$ Mev and intensity of 10^2 cm^{-2} sec^{-1}. sterad^{-1} were observed on 8th September along with the electrons. During measurements, the satellite stayed in the shadow of the Moon and the effect of solar X-ray radiation was thus eliminated.

According to Vampola [187], electrons of extremely high energies were recorded on September 2, 1966 by electron spectrometer of the "1966-70A" satellite launched into the polar orbit. Sharp changes in the spectrum and total flux of electrons were observed in the northern as well as in the southern polar regions. The differential spectrum in the energy range of 0.225-1.375 Mev was $\sim \mathcal{E}_k^{-2.02}$ on the subsolar side and $\mathcal{E}_k^{-2.77}$ on the antisolar side. The ratio of total fluxes of electrons in this energy range on the antisolar and subsolar sides of the transition zone was equal to 3.5 about 19 hours after the flares.

22.2. Propagation of solar electrons. As mentioned earlier, in 1965 Van Allen and Krimigis [128] recorded three increases in the flux of solar electrons with $\mathcal{E}_k \gtrsim 40$ kev. The time profile of the intensity of electrons during May 25-28 and June 5-7, 1965 was in general the same as that for solar protons with $\mathcal{E}_k \sim 20$ Mev and precisely the intensity abruptly (within a few hours) increases to the maximum value and gradually decreases (within 1-2 days).

The authors [128] were convinced to use the diffusion model of propagation of particles, suggested by Parker [I.6] and

TABLE 22.2

Results of measurements on solar electrons near the Moon [185]

Date of measurements	Energy, kev	Beginning of outburst, UT	Duration of the effect, min.	Maximum intensity, $cm^{-2}, sec^{-1}, sterad^{-1}$	Index of the integral spectrum
September 1, 1966	>30	19.02	15	1700	-2.5
	>60	19.02	15	300	
September 8, 1966	>30	07.37	3.5	4000	
	>60	07.37	3.5	200*	
	>300	07.40	0.42	1200	
September 8, 1966	>30	10.11	20	800	
	>60	10.11	20	300	-1.5

* Intensity not at the maximum but at the beginning of the outburst.

developed by Krimigis [IV.28] (for details of this model, see Section 14.6). The relation (14.45) was used for processing the experimental data and it was assumed that the diffusion coefficient of electrons does not depend on the distance from the Sun ($\beta = 0$).

The plot of the function $f(t) = \exp(-1/t)/t^{3/2}$, which is a term of the right-hand side of equation (14.15), is shown in Fig. 22.5 for $\beta = 0$ and the given value of r. Positions of maxima ($f' = 0$) and two points of inflection ($f'' = 0$) are also shown. Straight line, passing through the first point of inflection, describes the method of determining the time of commencement of the outburst t_o. If the time of emission of electrons by the Sun is denoted by $t_o = 0$, some idea on the value of t_o can be obtained on the basis of Fig. 22.5. Actually if $t_o = 0$, the intensity of electrons becomes maximum at $t_{max} = 0.667$ hrs while the commencement of outburst, as extrapolated for experimental data, corresponds to the value $t_o = 0.149$ hrs. Now, it is possible to write the expression.

$$\frac{t_{\max}-t_0}{t_{\max}-t_0'}=\frac{0{,}667}{0{,}518}=1{,}29.$$

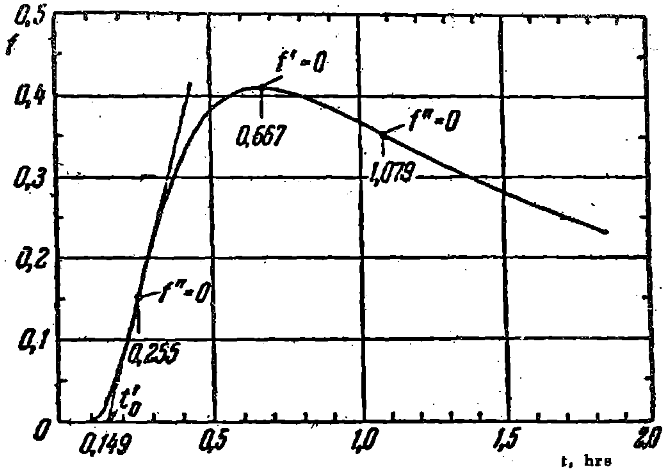

Fig. 22.5. Graph of the function $f(t) = \exp(-1/t)/t^{3/2}$.

For the May 25-28, 1965 events, $t_{max} - t'_o \approx 130$ min and $t_{max} - t_o$ can go up to 168 min while $(t_o - t_o')$ is less by 38 min only if the equation (14.45) correctly describes the diffusion process.

In general, diffusion coefficient and parameter β can depend on the energy of particles. However, in this case, a narrow energy range of width 15 kev is actually recorded due to large steepness of the energy spectrum of electrons and therefore, the beam can be considered to be monoenergetic.

Using the solution of equation (14.30), it is possible to estimate the number of emitted electrons N and the values of diffusion coefficient $\varkappa$.

Experimental data reveal a multipeak structure in about 6 hours after the commencement of the outburst for the May 25-28, 1965 event and in about 10 hours for June 5-7 event. Limiting the analysis to the period before the beginning of the multipeak structure, Van Allen and Krimigis [128] got the following values:

1. May 25-28, 1965. $\beta = 0 \pm 0.2$ for electrons with $\mathcal{E}_k \gtrsim 45$ kev and $\mathcal{E}_k \gtrsim 40$ kev; $t_o = 22.45^{+10}_{-5}$ U.T. on 25th May for the same energies; $N(\gtrsim 45) \sim 0.7 \times 10^{33}$ electron. sterad^{-1}; $N(\gtrsim 40) \sim 1.1 \times 10^{33}$ electron. sterad^{-1}; $\varkappa(\gtrsim 45) \sim \varkappa(\gtrsim 40) \sim 8 \times 10^{21}$ cm^2/sec.

2. June 5-7, 1965. $\beta = 0 \pm 0.2$ for electrons of both the threshold energies; $t_o = 18.55^{+10}_{-5}$ UT for the same energies; $N(\gtrsim 45) \sim 4.5 \times 10^{32}$ electron. sterad^{-1}; $N(\gtrsim 40) \sim 8 \times 10^{32}$ electron. sterad^{-1}; $\varkappa(\gtrsim 45) \sim \varkappa(\gtrsim 40) \sim 1.3 \times 10^{22}$ cm^2/sec.

The value $\beta = 0$ corresponds to the case when the effective diffusion coefficient does not depend on r. This result for electrons sharply differs from the results mentioned in Section 14.6 for protons during the period 1961-1963. It is interesting to mention that the application of diffusion model with $\varkappa \sim r^\beta$ to the data [129] gave the value $\beta = 1.2$.

The significant physical difference between electrons and protons lies in the difference of their Larmorov radius in the interplanetary magnetic field. As can be seen from Table 22.3, Larmorov radius of electron with $\mathcal{E}_k \sim 40$ kev is about 10^3 times lesser than that for proton in the region of energies studied usually and is approximately equal to 10^{-6} a.u. in the interplanetary medium.

TABLE 22.3

Larmorov radii of electrons and protons in the interplanetary field

Type of particles	$\mathcal{E}_k$, Mev	Magnetic rigidity, 1 γ. 1 a.u.	Larmorov radius in the field 5 γ, a.u.
Electrons	0.04	4.60×10^{-6}	0.9×10^{-6}
Protons	1	0.97×10^{-3}	0.2×10^{-3}
	10	3.05×10^{-3}	0.6×10^{-3}
	100	9.66×10^{-3}	1.9×10^{-3}
	1000	30.54×10^{-3}	6.1×10^{-3}

From this, it can be concluded that electrons apparently represent a valuable new medium for studying the structure of the interplanetary magnetic field. For example, scattering at magnetic irregularities of approximate size 10^{-4} a.u. must have an absolutely different nature for electrons of $\mathcal{E}_k \sim 40$ kev than for protons having $\mathcal{E}_k \sim 20$ Mev.

23. POSSIBILITY OF GENERATION OF NEUTRONS ON THE SUN

Possibility of generation of fast solar neutrons was discussed in a number of works (Haymes [131, 132], Simpson [133], Lingenfelter [134], Lingenfelter and Flamm [II.5; II.6]; Lingenfelter et al. [135, 136], Biswas and Fichtel [III.37], Apparao et al. [137], Hess [138], Chupp et al. [139], Hess and Starnes [140], Roelof [141], Bame and Asbridge [142]).

The following are some possible processes pointed out by Hess [138].

1. Generation under the action of cosmic rays. This source is negligibly small because the Sun consists of the lightest elements which do not have surplus neutrons. In principle, neutrons can be formed in the process $p+p \rightarrow \pi^{+}+n+p$, the threshold for which is of the order of 300 Mev. However, the extent of this reaction is very small.

2. Thermonuclear reactions in corona. The corona has a temperature of about 10^6 °K, ratio of deuterium atoms to hydrogen is approximately equal to 5×10^{-5} and therefore, reactions of the type of $D + D \rightarrow n + He^3$ are possible. Numerical calculations show that this can give a flux, on the boundary of the Earth's surface, of the order of 10^{-9} neutron.cm^{-2}.sec^{-1} which is negligibly small as compared to the flux of neutrons originating under the action of cosmic radiation. Neutrons can also originate in the Sun but probability of their exit outside is very small.

3. Formation of neutrons in the Sun's and Earth's atmospheres under the action of protons from solar flares. It is known that powerful fluxes of protons mainly with $\varepsilon_k < 100$ Mev reach polar regions of the Earth during certain flares. These fluxes exist for a long time ($\geqslant 10^4$ sec) and can exceed 10^5 cm^{-2}. sec^{-1} at an energy of more than 10 Mev. According to estimates of Hess [138], the emission of about 5×10^{30} protons by a solar flare during 1 sec corresponds to such a flux. Apparently, this very amount of protons is absorbed by the Sun, giving rise to a large number of neutrons. If it is assumed that every proton on an average gives rise to 0.01 neutron during interaction with the matter of the Sun, such a source must give, near the boundary of the Earth's atmosphere, a flux of about 10 neutron.cm^{-2}.sec^{-1} with $\varepsilon_k < 100$ Mev. Neutrons are not observed at the sea level but they can however be detected beyond the limits of the Earth's atmosphere.

Large fluxes of neutrons can originate in the Earth's atmosphere under the action of solar protons. According to the estimates of Hess [138], neutron flux from solar protons can be more than 10^4 cm^{-2}. sec^{-1} at the boundary of atmosphere in polar regions.

On November 15, 1960 during the flight of the American rocket "Atlas" at an altitude of 500 km over a station of latitude 40°S, Chupp et al. [139], with the help of a neutron monitor, recorded a three-time increase in neutron flux as compared to the earlier measurements of Hess and Starnes [140]. Such a phenomenon can be explained by the action of solar protons since a significant increase in the flux of charged particles from the Sun was recorded at that time. Apparently, had the experiment been conducted at higher latitudes, the observed effect would have been even stronger. It should be mentioned that according to the data obtained by Hess [138], the flux of activity is approximately equal to 0.3 neutron cm^{-2} sec^{-1} on the equator and 3 neutron.cm^{-2}.sec^{-1} near the poles. This flux is caused by neutrons escaping from the Earth's atmosphere.

The Moon can also be a source of neutrons. Under the action of cosmic radiation, a much larger number of neutrons must originate at the Moon than that in the Earth's atmosphere due to the following causes (Lingenfelter et al. [135]): 1. The moon has a very weak magnetic field and therefore, low-energy cosmic particles can reach its surface. 2. Neutrons originate in materials heavier than nitrogen and oxygen. 3. π-mesons, originating from high-energy particles, can play a significant role in the formation of neutrons during interaction with the material of the Moon while almost all π-mesons disintegrate in the Earth's atmosphere due to low density of air.

Owing to these factors, the rate of formation of neutrons in the material of the Moon must be about 10 times that in the Earth's atmosphere. A flux of about 10 neutron.cm^{-2}.sec^{-1} should be expected on the Moon's surface. At a depth of about 30 g/cm^2 below the lunar surface, the flux must be much more -- nearly of the order of 3000 neutron.cm^{-2}.sec^{-1}.

The neutron fluxes may significantly increase during solar flares. Near the Earth, neutron fluxes of the order of about $2x10^{-4}$ cm^{-2}.sec^{-1} should be expected from the Moon which is much less than that from the atmosphere. In the case of the presence of a significant content of hydrogen, a peak of thermal neutrons must be observed in the spectrum.

Simpson [133] as well as Lingenfelter and Flamm [II.5] assumed that neutrons may be emitted by the Sun even under quiet conditions. Solar neutrons can also originate during interactions of energetic protons and α-particles with thermal particles of the surrounding medium in the solar atmosphere. As is well known, neutrons are unstable particles and their half-life period is approximately equal to 17 minutes. Therefore neutrons, existing at the boundary of the Earth's atmosphere, can only be of solar or lunar origin since the probability of formation of neutrons due to interaction of cosmic rays with nuclei of the interplanetary medium is negligibly small.

According to estimates of Lingenfelter [135], the flux of solar neutrons with $\mathcal{E}_k > 10^7$ ev in the region of the Earth is 2-3 times the average total flux of albedo neutrons. Owing to the absence of electric charge, neutrons are not subjected to the action of magnetic fields and therefore, they move from the Sun in straight lines. It is clear from this that flux of solar neutrons near the Earth will be maximum at the subsolar point and must increase on increasing the distance from this point while flux of albedo neutrons will increase with an increase in the geomagnetic latitude owing to latitudinal effect of galactic cosmic rays.

It is difficult to detect solar neutrons because the existing measuring equipment is mainly sensitive to thermal and average-energy neutrons ($\mathcal{E}_k < 10^5$ ev) while solar neutrons can have $\mathcal{E}_k > 10^5$ ev but their flux in the region of thermal and average energies is apparently small as compared to the flux of albedo neutrons of same energies.

A method of measuring solar and atmospheric neutrons was studied by Pinkau [143]. Neutrons with $\mathcal{E}_k \approx 20\text{-}100$ Mev, capable of reaching the Earth, orginate on the Sun in the process of interaction of solar protons with the matter of the photosphere. At present, we do not have such measuring apparatus which would have sufficient resolving power with respect to directions and energy. Therefore, it is not possible to differentiate solar neutrons from albedo neutrons and to get energy spectrum. The author [143] suggests to utilize the principle of double scattering of neutrons on protons in the measuring apparatus. For this purpose, a substance with a high hydrogen content must be used in the recording system.

Inspite of the above-mentioned difficulties, Haymes [131] could record specific diurnal effect -- increase in the flux of neutrons immediately before setting of the Sun. Measurements were taken with the help of thermal-neutron detectors during three balloon flights. Two flights were conducted in

1958, i.e., at the time of maximum of the last solar cycle, and the third, near the maximum of the previous cycle. The recorded outbursts were possibly caused by low-energy secondary neutrons formed in the terrestrial atmosphere as a result of a nuclear chain-reaction which was caused by fast solar neutrons passing through the rapidly-increasing layer of the atmosphere between the detector and the Sun just before its setting.

The results of some other measurements can also be interpretted within the framework of Simpson's hypothesis [133]. Since there must be a surplus of solar neutrons as compared to albedo neutrons, this hypothesis can, in particular, explain the second maximum in the spectrum of protons of the internal radiation belt. This maximum was detected in the measurements of Freden and White [144] and was apparently caused by the effect of superposition of protons from fission of albedo and solar neutrons since the spectrum of only albedo neutrons must monotonously fall with an increase in energy.

Recently, Haymes [132] made an attempt to record continuous emission of solar neutrons with $\mathcal{E}_k \leqslant 20$ Mev. The measurements were taken in the stratosphere with the help of balloons. The comparison of the counting rates of the detector, made on the basis of diurnal and nocturnal changes, helped in getting the upper limit of neutron flux 200 $\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1}$ for $\mathcal{E}_k$ = 1-14 Mev. It should be mentioned that, if neutrons are generated on the Sun with energies right up to hundreds of Mev, high-energy neutrons have a higher probability of reaching the Earth's surroundings without disintegrating than the low-energy neutrons.

Changes of neutrons on March 23, 1962 in the stratosphere over Hyderabad, India (geographical latitude 17.3°N, longitude 78.5°E, vertical geomagnetic cut-off rigidity 16.9 Gv) are described in the work of Apparao et al. [137, 145]. The neutron flux in the range $\mathcal{E}_k$ = 4-160 Mev was determined on the basis of measurements of tracks of recoil protons in the process of elastic collisions of neutrons with hydrogen nuclei in photoemulsion. The low intensity of galactic cosmic rays, caused by high cut-off rigidity in the Hyderabad region, led to a low flux of secondary particles at the altitudes of balloon flights which facilitated recording the changes in flux of solar neutrons. Basic results of the experiment are described in Table 23.1.

Neutrons have been divided into two energy groups: $\mathcal{E}_k$ = 4-20 Mev and $\mathcal{E}_k$ = 20-160 Mev. The first group approximately corresponds to evaporative neutrons and the second to cascade neutrons. Digits in brackets denote the total number of observed events of a given type. It should be mentioned that the cases when the tracks had zenith angle more than 60° were neglected at the time of analysis.

It is seen from Table 23.1 that in the range $\mathcal{E}_k$ = 4-20 Mev, practically all the neutrons, coming downward, are of atmospheric origin while in the range $\mathcal{E}_k$ = 20-160 Mev, the number of atmospheric neutrons is only 15% of the observed number of neutrons moving downward. The actual surplus of neutrons is equal to 148 ± 60 $cm^{-2} \cdot sec^{-1}$ and the Sun is their most probable source. This conclusion agrees with the fact that flux of neutrons with $\mathcal{E}_k$ = 4-20 Mev is much less than in the range $\mathcal{E}_k$ = 20-100 Mev which is caused by much higher probability of existence of high-energy neutrons at a distance of about 1 a.u. from the Sun as compared to low-energy neutrons. A significant flux of low-energy neutrons can be observed near the Earth only in that less-probable case when generation spectrum of neutrons is very sleep.

It is appropriate to mention that, according to the recent calculations of Lingenfelter et al. [136], the flux of solar neutrons with $\mathcal{E}_k > 10$ Mev, expected near the Earth, is equal to 30 cm^{-2}, sec^{-1}. But these calculations were based upon a particular model with wide range of changes in the intensity of the emitted particles. Therefore, a direct comparison of the calculations [136] with the observation results [137] does not have any special significance.

Observations [137] were made at a ~~time when~~ the number of sunspots was maximum for the corresponding 27-day rotation of the Sun. Moreover, at 3 hours local time on March 23, 1962, a flare of class 3 was observed which did not lead to any effect in cosmic rays and to geophysical disturbances. The detector was at the limiting altitude of 10 g/cm^2 between 9-15

TABLE 23.1

Summary of the results of the experiment [137, 145] on detection of solar neutrons

Details of the experiment	$\mathcal{E}_k$ = 4 - 20 Mev		$\mathcal{E}_k$ = 20 - 160 Mev	
	flux upwards	flux downward	flux upwards	flux downwards
Total number of collisions per cm^3 of photoemulsion	13.9 ± 1.5 (85)	14.5 ± 1.5 (89)	6.5 ± 1.0 (40)	5.1 ± 0.9 (31)
Number of collisions during acending and descending of balloon per cm^3 of photoemulsion	3.3 ± 1.2 (8)	4.5 ± 1.3 (11)	2.9 ± 1.1 (7)	1.6 ± 0.8 (4)
Intensity of neutrons at an altitude with pressure 10 g/cm^2, m^{-2}, sec^{-1}, $sterad^{-1}$	70 ± 13	67 ± 14	117 ± 46	173 ± 60
Role of residual atmosphere over the detector, cm^2, sec^{-1}, $sterad^{-1}$		64		25
Flux of solar neutrons, m^{-2}, sec^{-1}		3 ± 14		148 ± 60

hours local time and therefore, the observed beam of neutrons was apparently related to active region of the Sun, responsible for the flare.

By analyzing the available experimental data and theoretical estimates of the flux of cosmic neutrons in various energy ranges, Biswas and Fichtel [III, 37] arrive at the conclusion that there is no sufficient and convincing proof of the existence of fast neutrons of solar origin.

In order to verify the assumption of continuous emission of neutrons by the Sun, in October 1963, Bame and Asbridge [142], with the help of "Vela" satellite, measured the intensity of solar neutrons at distances of 16-20 r_E. Data on counting rate of neutron detector during the eclipse of satellite by the Moon or the Earth were investigated. It was found that the flux of solar neutrons is very low and it lies beyond the threshold sensitivity of the equipment. If it is assumed that the spectrum of solar protons is similar to the spectrum of the Earth's albedo neutrons, the upper limit of the flux of solar neutrons will be equal to 0.01 $cm^{-2} \cdot sec^{-1}$. The possibility of appearance of outbursts of solar neutrons after chromospheric flares was also studied; two of these flares were of class 3 while many others were accompanied by radio outbursts of type IV. Increase in neutron flux was not observed in any of these events*.

One of the recent works on detection of solar neutrons was conducted by Daniel et al. [146] on April 15, 1966 with the help of a detector, which consisted of a scintillator and an arc chamber and was raised on balloons over Hyderabad (geomagnetic latitude 17.6°N). Neutron measurements at equator have a number of advantages (low background of neutrons from galactic cosmic rays, absence of latitudinal effect of solar neutrons, maximum intensity at subsolar point if the neutrons have solar origin).

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* *As pointed out by Bame et al. [188], neutron detectors on "Vela" satellite were capable of recording the increase in neutron intensity due to a solar flare which was 3% of the theoretical value for the large flare of November 12, 1960. Although the integral flux of charged particles from September 2, 1966 flare was about 10% of the flux for November 12, 1960 flare, increase in neutron intensity was not observed. It follows from this that either the fraction of charged particles, returning to the Sun's surface after their acceleration, is much less than 50% or they fall into the dense layers of the solar atmosphere gradually as a result of which increase in the intensity of neutrons lasts for a much longer period.*

Measurements [146] were taken starting from 210 mb level to 11 ± 1 mb level. At the limiting altitude, data were obtained during the 1.5 hours of recording. The flux of neutrons from the Sun was 3.35 times the background of galactic cosmic rays (at the limiting altitude) and was equal to 10^3 m^{-2} sec^{-1} in the range $\mathcal{E}_k$ = 50-500 Mev.

The authors [146] analyzed the possible causes of the high flux of neutrons on April 15, 1966 and arrived at the conclusion that it cannot be explained by instrumental errors or by strong variations of cosmic rays (according to simultaneous measurements with the help of Geiger counters on the same flight, significant variations were not observed during this period). It can be assumed that the increase in neutron flux was caused by a solar subflare in the spot group which appeared on the eastern limb of the Sun on April 12, 1966. At the time of measurements, increase in brightness of H_α line in this active region was observed which was accompanied by the ejection of chromospheric matter and increase in the intensity of radio emission at 100 MHz from 2×10^{-22} to 6×10^{-22} $w \cdot m^{-2}$ $hertz^{-1}$. Such phenomena of solar activity are usually classified as subflares.

Thus, the results of measurements [146] can apparently serve as the first proof of emission of high-energy neutrons ($\mathcal{E}_k$ = 50-500 Mev) by the Sun.

It should be mentioned that as a result of disintegration $n \rightarrow p + e^- + \tilde{\gamma}$ (according to measurements of A. N. Sosnovskii et al. [147], with an average life of τ = 1010 ± 25 sec in static system), most of the protons do not reach the Earth's orbit. At a distance of 1 a. u. from the Sun, the fraction of disintegrated neutrons having $\mathcal{E}_k$ = 10 Mev will be about 97% while it will be about 59% for neutrons with $\mathcal{E}_k$ = 200 Mev. In this case, protons obtained as a result of disintegration must give rise to typical effects.

The problem of time variation of the intensity of protons from chromospheric flares on the condition that they are generated in the interplanetary space as a result of disintegration of solar neutrons, was studied by Roelof [141]. The solution of diffusion equation for neutron concentration n (r, v) was found to be

$$n(r,\ v)=\frac{3\Phi(v)}{4\pi\Lambda v^2\tau}\left\{\frac{v\tau}{r}-\left(1+\frac{\Lambda}{v\tau}\right)\left[\frac{e^{-r,v\tau}v\tau}{r}-\int_{r/v\tau}^{\infty}\frac{e^{-z}}{z}dz\right]\right\},\quad(23.1)$$

where Φ (v) is the generation spectrum of neutrons of velocity v, τ is the half-life period of neutrons, r is the distance from the Sun and Λ is the mean free path for scattering of protons in the interplanetary space (it is assumed that Λ depends neither on r nor on v). On the basis of equation (23.1), it is possible to evaluate the upper limit of flux of neutrons from the Sun. If it is assumed that the flux of protons, observed on "IMP-1" satellite during December 1963-May 1964, is caused only by disintegration of neutrons, then at Λ = 0.05 a.u. in the range $\mathcal{E}_k$ = 20-75 Mev, the upper limit of flux varies from 8×10^{21} neutron.sec^{-1} Mev^{-1} at $\mathcal{E}_k$ = 20 Mev to 4×10^{22} neutron.sec^{-1} Mev^{-1} at $\mathcal{E}_k$ = 75 Mev. Roelof [141] shows that the existing observation data on solar protons at distances of 0.5-1.5 a.u. do not eliminate the possibility of the fact that about 10% of the recorded protons in the range $\mathcal{E}_k$ = 1-100 Mev originated as a result of disintegration of solar neutrons in the interplanetary space.

Let us mention some works related to the study of solar neutrons and γ-rays originating during nuclear reactions in the photosphere of the Sun.

On the basis of balloon measurements with the help of Cerenkov scintillation counters in August 1964 at Argentina (26°S, 65°W, cut-off rigidity 12.1 Gv) Webber and Ormes [148] found that the flux of solar neutrons with $\mathcal{E}_k > 100$ Mev, during quiet days, is not more than 24 neutron.m^{-2}.sec^{-1} (by assuming that differential spectrum of neutrons $\sim\mathcal{E}^{-2}$). The results of estimates, made on the basis of data of various authors, of the upper limit of the spectrum of solar neutrons have been summarized in [148].

Chupp [149] estimated the yield of neutrons and γ-rays as a result of nuclear reactions on the Sun. For February 23, 1956 flare, the flux of fast neutrons ($\mathcal{E}_k$ of the order of a few Mev), expected near the Earth's orbit, is of the order of 1.8×10^{-4} T neutron $cm^{-2}.sec^{-1}$ where T is the duration of bombardment of solar atmosphere by cosmic rays. At $T \sim 10^3$ sec, the flux of solar neutrons near the Earth will be comparable with the equatorial flux of albedo neutrons ($0.1\ cm^{-2}.sec^{-1}$). For a similar flare, the flux of γ-rays near the Earth's orbit will be of the order of 5 $quantum.cm^{-2}.sec^{-1}$ at $\mathcal{E}_\gamma \gtrsim 0.51$ Mev. The experimental requirements on measurement of such low fluxes of this radiation are discussed briefly. Bland [150] studied the means of verification of the hypothesis about the nuclear origin of rigid γ-rays from solar flares ($\mathcal{E}_\gamma > 50$ Mev). According to this hypothesis, π^0-mesons are formed in cosmic rays, accelerated during the flare, as a result of nuclear reactions. These mesons later on disintegrate into γ-quanta ($p + p \rightarrow p + p + \pi^0$, $p + \alpha \rightarrow p + \alpha + \pi^0$). The expected energy spectrum of γ-rays is discussed in brief. The existence of maxima whose position is mainly defined by the direction of motion of accelerated protons with respect to the line of sight is a characteristic feature of this spectrum. Three simple cases are studied: motion of solar protons along the line of sight towards the observer and in the opposite direction as well as isotropic distribution. Here, the maximum in the spectrum of γ-rays due to disintegration lies in the region of 115, 40 and 77 Mev respectively while its position weakly depends on the nature of energy spectrum of accelerated protons. This conclusion is illustrated on the example of power spectrum $D(\mathcal{E}) = D_0 \mathcal{E}^{-\gamma}$ at different values of γ. Thus, by determining the position of maximum in the spectrum of γ-rays for flares near the central meridian and near the limb, it is possible to get information on the nature of motion of accelerated protons. The possible experimental verification of the hypothesis with the help of satellites is discussed. In the opinion of the author, the main difficulty will lie in eliminating γ-rays of atmospheric origin.

It is mentioned in the work of Fazio [151] that the experiment on detection of γ- quanta with $\mathcal{E}_\gamma > 100$ Mev from the Sun (the equipment was mounted on "OSO-1" and "1962-3-1" satellites) gave negative results. The upper limit of the flux for quiet

Sun was $2x10^{-3}$ $cm^{-2}.sec^{-1}$ while it was of the order of 10^{-2} cm^{-2}, sec^{-1} during a flare of class 3 (March 22, 1962). Attention is drawn to the importance of the study of radiation in the range ε_{γ} = 1-10 Mev during flares. The emission in this range is associated with scintillation of C, N and O nuclei excited by nonelastic collisions with accelerated protons of solar cosmic rays.

Lavakare [152] briefly describes the results of theoretical and experimental investigations on solar neutrons conducted by various authors. Korff [153] reviewed in detail the modern state of the problem of neutrons in cosmic rays. Scanton and Spergel [154] estimated the intensity of neutrons originating in the Martian surroundings during bombardment of Mars surface and atmosphere by cosmic rays.

24. GENERATION OF COSMIC RAYS ON THE SUN AND PROBLEM OF LOCAL ORIGIN OF LOW-ENERGY COMPONENT OF COSMIC RAYS

Since earlier estimates gave a value 10^{24} - 10^{25} particles/sec (see I.13], Section 43.4) as the rate of generation of cosmic rays ($\varepsilon_k \gtrsim 10^9$ ev) by the Sun, the role of about 10^{11} usual stars, which could give in all 10^{35}-10^{36} particles/sec, was found to be insignificant as compared to generation of $\gtrsim 10^{41}$-10^{42} particles/sec necessary for keeping the normal level of the intensity of cosmic rays in the Galaxy. Now, with the availability of new data, we feel that negligence of the role of ordinary stars can hardly be so categorical and that additional analysis is necessary. Actually, it follows from the data, given in Chapter III, that many solar flares generate a large number of particles ($\gtrsim 10^{32}$-10^{33}) with sharply decreasing spectrum apparently extending to energies of a few Mev. The rate of generation of low-energy particles by the Sun ($\gtrsim 10^6$ ev) must be increased by a few orders as compared to the above-mentioned estimate of the flux of particles with $\varepsilon_k \gtrsim 10^9$ ev.

If the galactic field be more or less regular near the solar system, low-energy cosmic rays, observed in the solar system, should apparently come from comparatively close regions in a direction transverse to the field. Actually, if there is a more or less regular magnetic field H $\sim 7 \times 10^{-6}$ gauss in the disk of the Galaxy, Larmorov radius of particles with $\varepsilon_k \leq 10^{10}$ ev will be $\rho \leq 5 \times 10^{12}$ cm. The particles in such a field can propagate either along the lines of force or transverse to them as a result of drift due to irregularities of the field. The rate of drift $v_d \sim \rho / \ell \, v_\perp$ where ℓ is the size of irregularities and $v_\perp$ is the velocity of particles. If $\ell \sim 10$ nc $\sim 3 \times 10^{19}$ cm and $v_\perp \sim 10^{10}$ cm/sec, then $v_d \sim 10^3$ cm/sec and at a concentration of about 10^{-2} cm^{-3} of the gas in the disk, the life of protons $T_p \sim 10^{17}$ sec. Such protons can reach the Earth only from a distance L $\sim 10^{20}$ cm $\sim$ 30 nc.

In the case of propagation along the lines of force of the field, particles during $\sim 10^{17}$ sec can reach almost from every part of the Galaxy, i.e., practically, there will be one-dimensional propagation of particles. In this case, the local origin of even low-energy components of cosmic rays appears to be less probable (not to mention the high-energy particles). In the case of closed configuration of the regular magnetic field around the group of nearest stars (at a distance ~ 30 nc), the total number of cosmic particles in the volume (at a concentration of about 10^{10} cm^{-3} for $\varepsilon > 10^9$ ev around the solar system) will be of the order of 3×10^{50} particles. It follows from this that generation of $\gtrsim 3 \times 10^{33}$ particles/sec is necessary for keeping the stable state (it is considered that life of particles in this volume is definitely less than 10^{17} sec). Since there are about 10^5 stars in this volume, it comes to about 3×10^{28} particles/sec for every star.

As already mentioned, the flux of particles from the Sun with $\varepsilon_k > 10^9$ ev is apparently not more than 10^{24} - 10^{25} particles/sec. However, it is comparatively easy to provide the required flux of about 3×10^{33} particles/sec if it is assumed that the particles with $\varepsilon_k > 10^6$ ev, generated by the Sun, are further accelerated in the volume under reference, for example, by the energy of magnetized corpuscular beams, emitted from the stellar atmospheres.

It is possible that in the volume under reference the mechanism of acceleration in the arbitrarily-formed traps as well as the statistical mechanism come into play. However, high rates of motion of field irregularities and small mean free paths for scattering are necessary to make the statistical mechanism effective.

In order to increase the energy of a particle of mass M in the nonrelativistic region from ε_{ko} to ε_k, at the rate of accumulation of energy

$$\frac{d\varepsilon_k}{dt} = \frac{u^2}{\Lambda}\sqrt{2\varepsilon_k M} \qquad (24.1)$$

the time required is

$$t = \frac{(\sqrt{\varepsilon_k} - \sqrt{\varepsilon_{ko}})2\Lambda}{u^2\sqrt{2M}} = \frac{(v - v_0)\Lambda}{u^2}. \qquad (24.2).$$

If $\varepsilon_{ko} \sim 10^7$ ev, and $\varepsilon_k \sim 10^9$ ev, then at $\Lambda \lesssim 10$ nc $\sim 3\times10^{19}$ cm and $u \gtrsim 3\times10^6$ cm/sec, we get $t \lesssim 10^{17}$ sec $\sim T$. However, the particles cannot exist in a volume of dimensions L for such a long period (apparently, it is possible only in the presence of a strictly regular, closed magnetic field or in the case of very low mean free path Λ for scattering).

It should be taken into consideration that the time of acceleration is limited by the possibility of nuclear interaction (time T_n) as well as by the exit of particles from the above-mentioned volume owing to drifting at field irregularities and owing to diffusion during scattering at irregularities (time T_d). In order to quantitatively explain the observed abundance of Li, Be and B in galactic cosmic rays, it is necessary to assume that they, on an average, must cover a few g/cm^2 matter*. Therefore, if $n \sim 10^{-2}$ cm^{-3} it is necessary that $T_d \gtrsim 10^8$ years. But since $T_d \sim L^2/v\Lambda$, the transport range for scattering of particles $\Lambda \lesssim 10^{14}$ cm. At $u \gtrsim 3\times10^6$ cm/sec and $\varepsilon_{ko} \sim 10^7$ ev, according to equation (24.2), relativistic energies can be attained during $t \sim 10^4$ years. Thus, the problem is as to whether such low values of Λ are possible. There are strong arguments in favour of the fact that Λ in reality is significantly high (as an average for the Galaxy, it is usually assumed that $\Lambda \gtrsim 3 \times 10^{19}$ cm). But then $T_d \ll 10^8$ years owing to which Li, Be and B cannot be formed. At large values of Λ, still larger power of sources should be assumed.

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* *Here we base upon generally accepted confirmation that Li, Be and B have secondary origin, i.e., they were formed due to fragmentation of heavier nuclei during their motion in the interstellar medium.*

Measurements on $He^3/(He^3+He^4)$ *ratio in the interplanetary space also give information on the amount of matter, crossed by cosmic rays, on assuming that* He^3 *nuclei were formed due to fragmentation. Such measurements were taken by many research workers. One of the recent results was obtained by Biswas et al. [190]. According to estimates [190], multiple-charged nuclei cross about 7-9 g/cm*^{2} *of the interstellar matter at* $\varepsilon_k = 200$-300 *Mev/nucleon. These results do not contradict the estimates obtained from Li/M ratio (M-nuclei:* $6 \leq Z \leq 9$*).*

Moreover, high-energy particles (for example, $\mathcal{E} \gtrsim 10^{14}$ ev) cannot be retained in the volume of dimensions L and must be of galactic origin. If the existence of different sources for particles of different energies is assumed, it becomes difficult to "join" energy spectra.

In this case, the particles of solar origin do not play a significant role due to the following reasons (each of which is the deciding cause): due to rapid leakage of particles from chromospheric flares beyond the limits of the solar system; owing to significant difference in energy spectra of solar and galactic cosmic particles and finally, due to sharp differences in the nuclear composition of galactic cosmic rays and fast particles from chromospheric flares.

Moreover, as shown by experimental data (see Section 11), it is meaningful to talk of the role of solar particles only at $\mathcal{E}_k \lesssim 200$ Mev. As far as the spectra are concerned, it should be kept in view that, according to S.I. Syrovatskii [III.3], generation spectra, similar in shape, can be expected of different sources. But, since the intensity will be different and since every source gives beams of particles in different energy ranges, there must be points of inflection and breaks in the total spectrum obtained on summing up the spectra of points of inflection and breaks in the total spectrum obtained on summing up the spectra of solar and galactic cosmic rays).

Had the solar system existed in the Supernovo shell, there would had been a possibility of local origin of the main part of cosmic rays (of course, it would have been difficult to explain the presence of Li, Be and B in cosmic rays but this difficulty could have been overcome). In this case, it could have been expected that the intensity of cosmic rays in the Earth's surroundings is more than that in the Galaxy. But this position will be only temporary and after generation and scattering, the shell of the intensity of cosmic rays will be equalized. Thus, taking into account the results of the analysis of some meteoritic data (see [I. 2], Section 58.1), it can be confirmed that at present, the solar system hardly exists in the Supernovo shell. In any case, the present intensity of cosmic rays in the surroundings of the solar system is not more than 1.5 times the average intensity in the Galaxy.

Thus, the above-mentioned facts go against the assumption of local origin (in usual stellar atmospheres or in the Supernovo shell) of the main part of galactic cosmic rays, observed on the Earth. It should once again be underlined that it does not eliminate the possibility of solar origin of the least-energetic part of cosmic rays (with energy less than a few hundred Mev) during comparatively high solar activity in the presence of frequent chromospheric flares (see Section 11).

25. SOLAR COSMIC RAYS AND RADIATION DANGER

Protons from solar flares represent maximum radiation danger to astronauts during flights in the interplanetary space (see, for example, the review of I. M. Savenko et al. [155] or collection of articles [156]).

Attempts were made in a number of works to estimate the value of radiation dose from many solar flares. Even at the existing level of knowledge on solar cosmic rays, and on the basis of these estimates, it is possible to recommend the optimum characteristics of the shield required for protecting the astronauts.

The nature and depth of irradiation of any material by fast particles significantly depends on their energy spectrum. Since, for most of the flares, the spectrum of solar cosmic rays is very soft, only unprotected or weakly-protected parts of the astronaut's body (skin, crystalline lens of the eye, etc) will be subjected to radiation in open space.

On the basis of this, Waddington [157] suggested to classify flares of solar protons into two types -- A and B -- depending upon the type of spectrum. Flares of type A are characterized by integral spectrum of the type $\sim \mathcal{E}_k^{-4}$ in the range $\mathcal{E}_k = 30\text{-}400$ Mev and cannot be detected from the increase in the intensity on the Earth's surface. They are usually recorded during measurements on balloons, rockets and satellites. Frequency of this type of flares is sufficiently high for example, nearly 40 events were observed during July 1957-November 1960. Flares of May 10, 1959, November 12, 1960 and others can be put in the category of flares of type A.

Flares of type B are characterized by the integral spectrum of the form $(\mathcal{E}_0 + \mathcal{E}_k)^{-6}$ and are recorded on the Earth's surface. Flares of this type, in general, are very rare. A typical flare of type B occurred on February 23, 1956.

Winckler et al. [I. 65] evaluated radiation dose at the boundary of the atmosphere and in the interplanetary space during quiet days and during some flares of cosmic rays (Table 25.1). It should be mentioned that radiation doses, mentioned in this Table and obtained by exptrapolating the stratospheric data, are apparently very high because it was assumed that the form of the spectrum does not change on transiting to low energies (actually, the index of the spectrum in many cases decreases significantly on transiting to $\mathcal{E}_k \lesssim 100$ Mev).

Data on absorption of radio waves in the region of polar caps were compared by Bailey [95] with the results of measurements on balloons, rockets and satellites with the aim to study time variations of the spectrum of solar protons.

The integral intensity of particles having $\mathcal{E}_k \geqslant 100$ Mev is of utmost interest since particles of lesser energies will be effectively absorbed by the shield of the spaceship. It is seen that radiation flux becomes maximum 8-16 hours after the commencement of flare and significantly decreases after 32 hours (Fig. 25.1). Obviously, the maximum intensity of protons with $\mathcal{E}_k \geqslant 100$ Mev, from most of the flares, is not more than $2\text{x}10^2\text{-}5\text{x}10^2$ $\text{cm}^{-2} \cdot \text{sec}^{-1} \cdot \text{stered}^{-1}$ which is comparable to the radiation intensity in the Earth's internal radiation belt. According to Waddington [159], the maximum flux of protons

TABLE 25.1

Fluxes of galactic and solar cosmic rays from measurements on balloons and in the interplanetary space

Method of measurements	Period of measurements, UT	Flux of particles, cm^{-2}, sec^{-1}	Dose, roentgen/hrs.	Cosmic rays
Interplanetary space ("Pioneer-5" rocket)	March 11-23, 1960	4.6	0.0006	Galactic (10^8-10^{17} ev)
	12.00 April 1, 1960	33	0.026	Solar (40-500 Mev)
Balloons	12.00 April 1, 1960	0.4	0.0004	Solar (90-500 Mev)
Extrapolated for interplanetary space on the basis of balloon data	11.00 July 15, 1959	1.76×10^4	9.1	Solar (40-500 Mev)
	06.00 July 14, 1959	1.5×10^7	7.6×10^3	Solar (40-500 Mev)

with $\mathcal{E}_k \gtrsim 500$ Mev from most of the flares, giving rise to large outbursts on the Earth's surface, is of the order of 10^8 $\text{cm}^{-2}\cdot\text{sec}^{-1}$ and during the whole of the flare, it goes up to 3.6×10^{11} proton/cm^2.

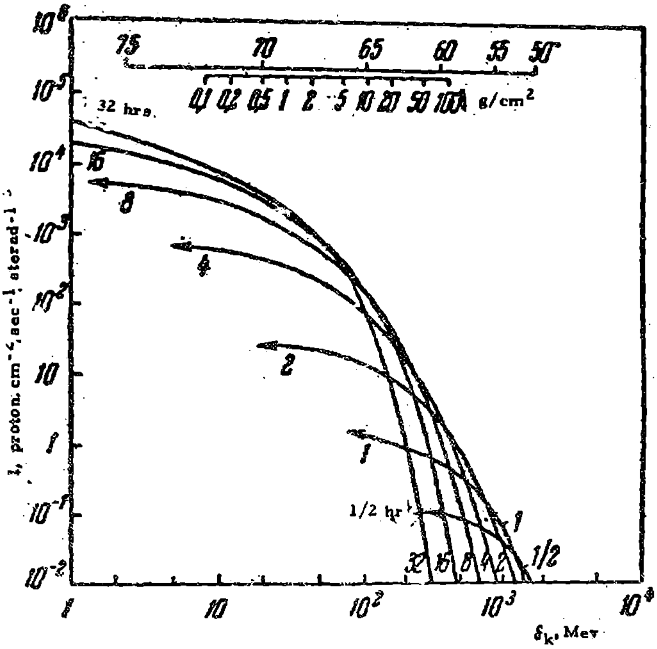

Fig. 25.1. Expected change in integral energy spectrum of solar protons with time after chromospheric flare (time is shown in hours). Geomagnetic cut-off latitudes and absorption ranges are given.

In order to safeguard the flight during such a flare, a shield of about 400 g/cm^2 carbon is necessary (in the case of prolonged flights in the interplanetary space, fuel reserve is suggested to be used as the shield). The frequency of such flares is so small (1 flare after many years) that short flights (for example, to Moon and back) are practically safe at shield thickness of about 5-10 g/cm^2 (from ordinary flares). However, in the case of flights to Mars or Venus, danger from the most powerful flares increases significantly.

Appleman [158] conducted a similar investigation on the problem of the possibility of manned flights in cosmic space in the presence of different types of radiation (galactic cosmic rays, radiation from the quiet Sun, radiation from chromospheric flares, Earth's radiation belt). It is shown that the first radiation sources are not harmful for man. During chromospheric flares, the total radiation dose in cosmic space can go up to tens and hundreds of roentgen. Radiation danger changes significantly with the cycle of solar activity.

The degree of radiation danger of galactic and solar cosmic rays as well as of radiation in the Earth's radiation belt is evaluated in the work of Masley and Goedeke [159]. The galactic radiation in cosmic space, on an average, gives integral radiation dose of about 5 rad/year. At the same time, the radiation dose at the center of the internal radiation belt goes up to 0.1 rad/hr. In the case of intersection of the internal radiation belt during one hour (at the equator), the dose attains a value of about 6 rad. During certain chromospheric flares, accompanied by generation of relativistic protons, radiation dose may go up to $2\text{x}10^2$ rad (November 12, 1960) and even up to $3\text{x}10^4$ rad (July 14, 1959).

Robey [160] points out that action of solar cosmic rays from class 3 and 3^+ chromospheric flares is the most harmful for an astronaut. By studying the phenomena accompanying these flares, the author [160] evaluates the degree of reliability of forecasting. By using the data on energy spectrum, intensity and time variations of large flares of solar cosmic rays, Robey calculates the most optimum dimensions of the shield necessary for protecting man from radiation dose harmful for him.

It is most appropriate to use carbon as the protective shield. An additional layer of lead or iron is suggested for protection from X-rays of braking radiation from electrons. From outside, an interplanetary spaceship can be covered by a thin layer of a synthetic material (polyethelene) which sharply reduces the intensity of braking radiation. The thickness of carbon shield required for reducing the radiation dose to 1-6 rem, has been calculated for the May 10, 1959 flare of cosmic rays. In the case of power spectrum of flare particles with index $\gamma \approx 6.8$, the thickness of the shield is equal to 22 cm (50 g/cm^2). However, during a cosmic-ray flare similar to the February 23, 1956 flare, safe radiation dose (less than 25 rem) will be achieved by carbon shield of thickness $\sim$ 260 cm. In this case, spherical shield of internal radius 90 cm will weigh about 379 tons. Here, the contribution of secondary neutrons and mesons has not been taken into account.

On the basis of the method, suggested by the same authors, V.E.Dudkin et al. [161] calculated the protection from solar protons for November 12, 1960 and February 23, 1956 flares belonging to types A and B respectively. For the November 12, 1960 flare, spectra for three periods of time were used (time in hours after the commencement of the flare): 1-10, 10-14 and 14-32 (see the review of Foelsche [163]). The total radiation dose during the flare was determined by summing up the doses corresponding to these periods of time. The energy spectra, measured at the beginning of the flare and after 19 hours, were used for the February 23, 1956 flare.

It was assumed in the calculations that cabin of the spaceship is spherical and is made of aluminum. The angular distribution of protons from solar flares was taken to be isotropic. A comparison of calculation results for the two above-mentioned flares shows that the average and local doses differ significatly: local dose is more by 10 times for the November 12, 1960 flare and by 7 times for February 23, 1956 flare at protection thickness of 1 g/cm^2 and by 2.3 and 1.2 times respectively at a thickness of 20 g/cm^2.

The dependence of absorbed tissue dose on depth was also calculated for these two flares at various thicknesses of the protection. It was shown that, if the thickness is more than 8 g/cm^2, drop from the maximum absorbed dose to the average tissue dose does not exceed 6. As shown by authors [162], this fact makes it possible to use the average tissue dose as the criterion of radiation safety in calculations of protection.

The absorbed depth doses were calculated in rad as well as in rem while in the latter case, use was made of the dependence of relative biological effectiveness (RBE) on linear energy losses, obtained by Langham [164] and Snyder and Neufeld [165] as applicable to the conditions of chronical action. The ratio of average tissue doses in rems and rads gives the value of RBE for the whole body. Although, due to absence of data, the maximum values of RBE for chronical action were used, in the calculations of depth doses, RBE for the whole body was found to be very low, differing from unity (at a protection thickness of more than a few grams per centimeter square). If it is considered that, in the case of sharp-ray actions which include radiation of protons from solar flares, the values of RBE are always much less than those in the case of chronical actions, then it follows that it is possible to express average tissue doses in terms of rad in the calculations of a protection from solar-flare protons.

The values of average tissue doses were obtained without taking into account the contribution of secondary particles, formed in the protection. Approximate extreme estimates of the contribution mentioned by Beck and David [166], show that role of secondary charged particles, formed by solar-flare protons in the protection, can be neglected. The role of secondary neutrons was found to be more significant for flares of type A. If the thickness of aluminum shield is of the order of 10 g/cm^2, the dose from secondary neutrons is found to be comparable to the dose from primary protons.

The calculated values of the average tissue doses from solar protons once again show that solar flares give rise to serious radiation danger owing to which it is necessary to foresee a special protection on spaceships. At the same time, it should be mentioned that previous estimates of radiation danger, associated with solar flares (see the works of Robey [160], Foelsche [163], Beck and David [166], Dye and Noyes [167]), were found to be very high since they were based on calculation of local absorbed doses. Moreover, it is necessary to point out that the finite probability of exposure of an astronaut to protons from many solar flares was not taken into account in calculations [160, 163, 166, 167]. V.E.Dudkin et al. [161] evaluated this effect by making use of the following factors.

For comparatively small intervals of time, the appearance of solar flares can be considered as statistically independent events. Appearance of a specific type of flare during the flight of a spaceship is an arbitrary event whose probability depends on the frequency of this type of flares as well as on the duration of the flight.

The probability of a given number of solar flares during a flight can be described by Poisson's law. The calculated probabilities of appearance of flares are given in Table 25.2 depending upon the duration of the flight; it was assumed in calculations that the frequency of flares corresponds to $\nu = 0.03$ day^{-1} for flares of type A and $\nu = 0.0011$ day^{-1} for flares of type B.

It may be seen from Table 25.2 that in the case of space flights of duration more than 10 days, it is necessary to take into account the danger of the effect of proton beam, from many solar flares of type A, on the astronaut. Thus, if a flight lasts for about 20 days, the probability that such a flare may not occur is only 55% while the probability of one flare is 33% and that of the two and three flares is 10% and 2% respectively. Obviously, while designing protection from protons for such flights, it is necessary to consider at least two solar flares of type A in the calculations of the protection. If, in this case, 50 rem is taken as the permissible radiation dose during the flights, the required thickness of aluminum protection is about 10 g/cm^2 in place of 4 g/cm^2, necessary for the protection from protons of one flare.

The probability of exposure of astronaut to protons of not only two but of three or more flares is significant in the case of space flights lasting for a few months. At the same time, the probability of the occurrence of solar flares of type B also becomes significant. It should, however, be mentioned that if probability of many flares of type A is taken into account in calculations of the protection, i.e., if thickness is taken more than 10-15 g/cm^2, radiation dose due to protons from a flare of type B is reduced to a great extent.

Application of some "criterion of risk" can be another possible method of estimating radiation danger from protons of many solar flares. The 5% probability of exposure of astronaut to dose of more than 5 rem by limiting the probability of radiation dose more than 200 rem to 0.5, was taken as such criterion by V.E. Dudkin et al. [161]. On the basis of the calculated average tissue doses and data of Table 25.2, it was found that a protection thickness of about 10 g/cm^2 is required for flights lasting, for example, up to 20 days. Thickness of 20 g/cm^2 is necessary for flights lasting, for example, for 100 days.

TABLE 25.2

Probability of solar flares at different durations of flight, % [161]

Number of flares, N	Solar flares of type A								Solar flares of type B						
	Duration of flight, days														
	1	5	10	15	20	50	100	200	1	10	50	100	200	365	730
0	99,7	86,1	74,1	63,8	54,9	22,3	5,0	0,2	99,9	98,9	94.9	89,6	80,2	66,9	44,8
1	2,99	12,9	22,2	28,7	32,9	33,4	14,9	1,49	0,1	1,1	5,2	9,8	17,7	26,9	36,0
	0,45	0,97	3,33	6,45	9,88	25,1	22,4	4.46	—	—	0.14	0,54	1,9	5,39	14,4
3	—	0,1	0,4	0,97	1,98	12,5	22,3	8,92	—	—	—	0,02	0,14	0,72	3,86
4	—	—	—	—	0,30	4.70	16,8	13,4	—	—	—	—	—	0,07	0,78
5	—	—	—	—	—	1,41	10,1	16,1	—	—	—	—	—	—	—
6	—	—	—	—	—	0,35	5,04	16,1	—	—	—	—	—	—	—
7	—	—	—	—	—	—	2,16	11,8	—	—	—	—	—	—	—
8	—	—	—	—	—	—	—	10,3	—	—	—	—	—	—	—
9	—	—	—	—	—	—	—	6,9	—	—	—	—	—	—	—

These data refer to the period of maximum solar activity. In the case of minimum solar activity, these data should be taken as upper limits.

Changes in physical characteristics and quantitative composition of the beam of particles during their passage through the protection, form the base of biological action of corpuscular radiation which includes protons of solar flares and the Earth's radiation belts. This, in its turn, assumes the significant difference in the reaction of radiation on different organs of a person since basic part of the protons, which had overcome the protection, will have mean free path less than the effective dimension of human body. To this end, V. S. Morozov et al. [168] made an attempt under laboratory conditions to estimate the change in biological effectiveness during passage of heavy nuclei right up to the moment of their stopping. Mice, arranged in rows perpendicular to the axis of monochromatic beam of protons with $\mathcal{E}_k$ = 120 Mev, were taken as the model of biological "cell" of living organism. They were exposed to 50 rad/min dose for 32 minutes by proton-synchrotron at Dubna. Survival rate and average life of dead creatures at different moments after exposure were determined. Graphs of the dependence of life (at 30th day) and survival rate of mice on 5th day after radiation are given. As a result of this experiment, it was established that the physical protection under certain conditions can become a factor aggravating the effect of cosmic radiation.

Orbital flights and biological experiments make it possible to estimate the radio-biological conditions at altitudes of 180-320 km. V. V. Antipov et al. [169] assume that during two-week flight to the Moon, the integral dose from primary cosmic rays, due to natural and artificial radiation belts of the Earth, goes up to 10 rem in the case of a protection of thickness 1-2 g/cm^2. Protons of a solar flare can be a source of overexposure of astronaut. The probability of falling into a radiationally dangerous flare during flight to the Moon and back, lasting for 1 week, is equal to 16% for solar flare of the type August 22, 1958, 5.8% for flare of the type July 10, 1959 and 0.3% for flare of the type February 23, 1956. A protection of thickness 3 g/cm^2 reduces integral dose during flare of the type August 22, 1958 to the permissible level of 25 rem but physical protection from flares of the type July 10, 1959 and February 23, 1956 still remains a technically unsolved problem. Danger of proton radiation must be reduced by modernizing the methods of forecasting a solar flare and by raising the stability of organisms of astronauts with the help of medicines.

Measurements, taken by Watt [170], on the flux and spectrum of neutrons at sea level, during minimum solar activity at the observation post 55°02'S, 3°21'W, give a value of 11.8+1.0 rem/year as the power of equivalent dose of neutron radiation in an insulated small piece of biological tissue. The equivalent dose, obtained by a semi-infinite layer of biological tissue of thickness 20 cm on irradiating it by an isotropic beam of neutrons at sea level, changes from (6.2+0.5) mrem/year on the tissue surface to ~ 3.5 mrem/year at a depth of 10 cm. The average surface dose of neutrons, received by personnel of supersonic planes flying at an altitude of about 20 km over the region of polar latitudes, fluctuates within the range 0.20-0.40 mrem/hrs depending upon the period of maximum or minimum solar cycle. The calculation results of doses are in agreement with the corresponding experimental values of doses, measured with the help of special neutron dosimeters.

The problem of exposure of astronaut's organism in diving suit outside the spaceship is discussed in the work of Schaefer [171]. At low shielding (0.1-0.2 g/cm^2), α-particles and heavy particles of solar corpuscular spectrum also become a source of radiation in addition to protons. Basing upon the analysis of composition and intensity of the flare of corpuscular radiation of November 12, 1960, it is concluded that the main action of corpuscular radiation is caused by α-particles up to a penetration depth of 0.5 cm in the organism tissue.

The work of Levy and Janes [172] is of great interest in which principally new types of shields--magnetic and plasma shields-- are studied.

During flights along orbits near the Earth (excluding polar orbits), astronauts are protected from protons of solar flares by the Earth's magnetic field. In the case of deeper penetration in cosmic space, a special protection of the crew of spaceship from solar protons is necessary. Layers of protective material, magnetic or electrostatic field around the ship of plasma protection can be used as such a shield. The thickness of material shield from protons with $\mathcal{E}_k = 30$, 100 and 200 Mev corresponds to 1, 10 and 30 g/cm^2 respectively. A detailed analysis of the weight of shield by magnetic field, generated by the electromagnet of superconducting material, shows that it is not less than the weight of material shield. Protection from protons by electrostatic field is practically impossible due to large consumption of energy required for deflecting electrons, accelerated by this field, from the ship. The principles of electrostatic protection from protons are combined in the plasma radiation protection with the magnetic field, created around the ship, in the form of a shield for electrons. The intensity of magnetic field, required in this case and the corresponding weight of the magnetic system are much less than those in the case of only magnetic shield from protons of solar flares. In the case of a toroidal ship, penetration of electrons through "holes" in the magnetic field, similar to the poles on the Earth, can be neglected completely. Crossed magnetic and electric fields are formed around the ship. The trajectories of electrons, trapped by them, have the form of spirals around the magnetic lines of force. The ship, having positive charge, in this case, will be surrounded by a cloud of electrons of equal charge. Basic parameters of plasma shield are estimated by assuming that electrical potential on a ship of maximum diameter 10 m has a value of 200,000 kv. From the condition of stability of magnetic field, minimum value of magnetic induction must be of the order of 2660 gauss. If current density in electromagnet of a superconducting material is 100,000 amp/cm^2, its weight will be 550 kgf and the current will be equal to 2×10^6 amp. On considering the weight of cryogenic system (180 kgf), the total weight of the electromagnetic unit becomes 730 kg and power of the unit will be 36 kw.

Works of Haffner [173], Vette [174], Dole [175], reviews of Admas and Mar [178], Shelton [179] and Keller [180] are also devoted to the problems of radiation safety. In these works, basic aspects of the physics of interaction of charged particles with matter are discussed, methods of calculating a shield are described, doses are estimated, etc. Here, the total effect of the Earth's radiation belts, solar protons and galactic cosmic rays is usually considered. Limiting to the analysis of works on radiation danger only from solar cosmic rays, we have not described the results, obtained in [173-180]. We have also not considered the results of numerous estimates of radiation doses, obtained during flights of Soviet and American astronauts.

In the end, it should be mentioned that the current information on solar flares (frequency, spectrum of protons, angular distributions, etc.) is insufficient to correctly explain radiation danger and the shield thicknesses required for the living compartments of spaceships. More investigations in this direction as well as elaboration of reliable methods of long-term forecasting, radiation warning and dosimetry are necessary.

CONCLUDING REMARKS

It can be concluded from previous Chapters that, by this time, certain successes have been achieved in the study of solar cosmic rays: charge composition, energy spectrum and nature of distribution of solar particles in the interplanetary space have been explained in general terms; a relation between emission of fast particles and radio and X-ray radiations of the Sun has been established; significant role of solar cosmic rays in some geophysical phenomena (especially, in the absorption of short radio waves in polar caps) has been shown; possible mechanisms of acceleration of particles on the Sun have been studied.

However, details of the processes studied above remain unexplained in many respects. It is explained by dynamic nature of the object or investigation, insufficient accuracy of measuring equipment, methodical difficulties, and by strong variability, with time and in space, of electromagnetic conditions on the Sun, in the interplanetary medium and in the Earth's surroundings.

Special difficulties arise on studying processes associated with generation of fast particles and with their exit from the acceleration region. Owing to detection of protons with energies $\mathcal{E}_k \sim 1$ Mev, which exist in the interplanetary space during many revolutions of the Sun, there arises the problem to find satisfactory mechanisms of their continuous generation or prolonged emission. In the case of protons with $\mathcal{E}_k > 1$ Mev, duration and time variation of emission are very significant for their spatial-time distribution in the solar system. The problem of prolonged emission of solar particles of extremely high energy has been studied insufficiently. The problem of angular characteristics of a pencil of emitted particles has not been studied at all. In particular, the study of the possible dependence of flight angle on the particle energy is of great interest. The possible ejection of corpuscular beam owing to the pressure of solar cosmic rays with their subsequent adiabatic cooling remains unexplained to a large extent.

The problem of formation of charge and energy spectra of solar cosmic rays, in particular, the problem of acceleration of nuclei which are not completely ionized requires further investigation.

In many cases, diffusion consideration of the motion of fast solar particles in the interplanetary magnetic fields is fully suitable for studying the general characteristics of the source of particles, their spectrum and properties of magnetic irregularities. A more strict approach gives kinetic consideration which, in particular, facilitates the study of the initial anisotropic stage of flares of solar cosmic rays and determination of properties of irregular magnetic fields (mainly in the Earth's orbit) from the angular characteristics of the beams of solar cosmic rays. However, application of the kinetic model to the analysis of energy spectrum of solar particles is still associated with great methodical and mathematical difficulties.

The problem of the exit of solar particles from the limits of the solar system is of great interest. This problem is associated with the possible existence of a semi-transparent magnetic barrier in the interplanetary space at a distance of 2-5 a.u. from the Sun. It is also not eliminated that scattering properties of the interplanetary fields weaken quickly on increasing the distance from the Sun which is proved by the dependence of diffusion coefficient on distance, observed in a number of works. It is worthwhile to study the problem of exit of trapped particles from the semi-transparent trap of solar corpuscular beam.

Great possibilities of experimental study of solar cosmic rays are, at present, opened owing to significant increase in the accuracy of ground equipment and development of techniques for direct measurements in the interplanetary space. Recording of solar particles in a wide range of energies during prolonged flights of cosmic probes along with the complex of ground measurements on cosmic rays and geophysical data facilitate the study of "fine structure" of the interplanetary magnetic field. A stationary, continuously-functioning automatic station on the Moon's surface can provide very valuable information on solar cosmic rays.

The problem of forecasting of solar flares in general and flares accompanied by strong flux of fast particles, in particular, has not yet been solved. It follows from this that reliable estimates of the thickness of protective shields are necessary for providing radiation safety to astronauts during prolonged flights to other planets of the solar system. Rough calculations, so far made on the basis of existing data, give extremely large thicknesses which make spaceships extremely heavy. To this end, there arises the problem of elaborating protection methods which could utilize parts of the ship (mobile shields, special radiation covers, fuel tanks, change in orientation of the ship, etc.) as the shield. Obviously, for this purpose, there is a necessity of new computations of harmful doses and shield thickness, based upon consideration of the peculiarities of propagation of solar cosmic rays change of their time variations and energy spectrum. With the help of such data, special dosimetric apparatus responding to the rate of change of radiation intensity as well as programed units containing necessary information on permissible doses can help the crew of a spaceship in every concrete case to select the optimum variant of the shield.

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CHAPTER I

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